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13/041,934 7 March 2011 (07.03.2011) US(71) Applicant (for all designated States except US): **APPLE INC.** [US/US]; 1 INFINITE LOOP, M/s 36-2pat, Cupertino, CA 95014 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **JIN, Nanbo** [CN/US]; 10400 Ridgeview Court, M/s RC08, Cupertino, CA 95014 (US). **PASCOLINI, Mattia** [IT/US]; 1 Infinite Loop, M/s 35-1mp, Cupertino, CA 95014 (US). **MOW,****Matthew, A.** [US/US]; 1 Infinite Loop, M/s 35-1MP, Cupertino, CA 95014 (US). **SCHLUB, Robert, W.** [AU/US]; 1 Infinite Loop, M/s 35-1MP, Cupertino, CA 95014 (US). **CABALLERO, Ruben** [CA/US]; 1 Infinite Loop, M/s 35-1MP, Cupertino, CA 95014 (US).(74) Agent: **TREYZ, G., Victor**; TREYZ LAW GROUP, 870 Market Street, Suite 984, San Francisco, CA 94102 (US).

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(54) Title: TUNABLE LOOP ANTENNAS

(57) Abstract: Electronic devices are provided that contain wireless communications circuitry. The wireless communications circuitry may include radio-frequency transceiver circuitry and antenna structures. A parallel-fed loop antenna may be formed from portions of a conductive bezel and a ground plane. The antenna may operate in multiple communications bands. The bezel may surround a peripheral portion of a display that is mounted to the front of an electronic device. The bezel may contain a gap. Antenna feed terminals for the antenna may be located on opposing sides of the gap. A variable capacitor may bridge the gap. An inductive element may bridge the gap and the antenna feed terminals. A switchable inductor may be coupled in parallel with the inductive element. Tunable matching circuitry may be coupled between one of the antenna feed terminals and a conductor in a coaxial cable connecting the transceiver circuitry to the antenna.

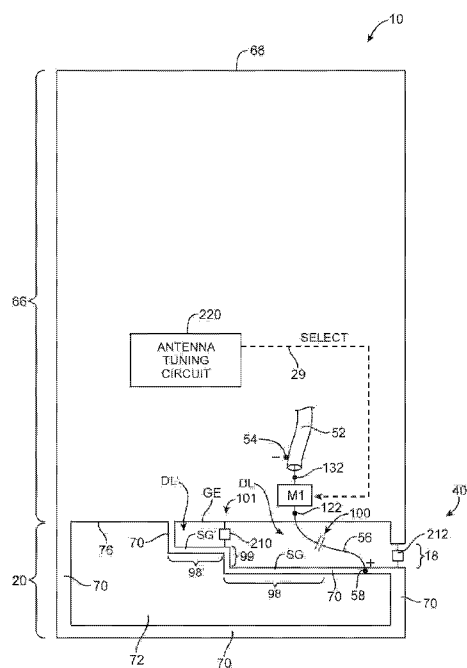


FIG. 13



GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD,
RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ,
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Tunable Loop Antennas

This application claims priority to United States patent application No. 13/041,934, filed March 7, 2011, which is hereby incorporated by reference herein in its entirety.

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Background

This relates generally to wireless communications circuitry, and more particularly, to electronic devices that have wireless communications circuitry.

10 Electronic devices such as handheld electronic devices are becoming increasingly popular. Examples of handheld devices include handheld computers, cellular telephones, media players, and hybrid devices that include the functionality of multiple devices of this type.

15 Devices such as these are often provided with wireless communications capabilities. For example, electronic devices may use long-range wireless

communications circuitry such as cellular telephone circuitry to communicate using cellular telephone bands at 850 MHz, 900 MHz, 1800 MHz, and 1900 MHz (e.g., the main Global System for Mobile Communications or GSM cellular
5 telephone bands). Long-range wireless communications circuitry may also handle the 2100 MHz band. Electronic devices may use short-range wireless communications links to handle communications with nearby equipment. For example, electronic devices may communicate using the WiFi®
10 (IEEE 802.11) bands at 2.4 GHz and 5 GHz and the Bluetooth® band at 2.4 GHz.

To satisfy consumer demand for small form factor wireless devices, manufacturers are continually striving to implement wireless communications circuitry such as
15 antenna components using compact structures. However, it can be difficult to fit conventional antenna structures into small devices. For example, antennas that are confined to small volumes often exhibit narrower operating bandwidths than antennas that are implemented in larger
20 volumes. If the bandwidth of an antenna becomes too small, the antenna will not be able to cover all communications bands of interest.

In view of these considerations, it would be desirable to provide improved wireless circuitry for
25 electronic devices.

Summary

Electronic devices may be provided that include antenna structures. An antenna may be configured to
30 operate in first and second communications bands. An electronic device may contain radio-frequency transceiver circuitry that is coupled to the antenna using a transmission line. The transmission line may have a positive conductor and a ground conductor. The antenna

may have a positive antenna feed terminal and a ground antenna feed terminal to which the positive and ground conductors of the transmission line are respectively coupled.

5 The electronic device may have a rectangular periphery. A rectangular display may be mounted on a front face of the electronic device. The electronic device may have a rear face that is formed from a plastic housing member. Conductive sidewall structures may run
10 around the periphery of the electronic device housing and display. The conductive sidewall structures may serve as a bezel for the display.

 The bezel may include at least one gap. The gap may be filled with a solid dielectric such as plastic.
15 The antenna may be formed from the portion of the bezel that includes the gap and a portion of a ground plane. To avoid excessive sensitivity to touch events, the antenna may be fed using a feed arrangement that reduces electric field concentration in the vicinity of the gap.

20 An inductive element may be formed in parallel with the antenna feed terminals, whereas a capacitive element may be formed in series with one of the antenna feed terminals. The inductive element may be formed from a transmission line inductive structure that bridges the
25 antenna feed terminals. The capacitive element may be formed from a capacitor that is interposed in the positive feed path for the antenna. The capacitor may, for example, be connected between the positive ground conductor of the transmission line and the positive
30 antenna feed terminal.

 A switchable inductor circuit may be coupled in parallel with the inductive element. A tunable matching circuit may also be interposed in the positive feed path for the antenna (e.g., the tunable matching circuit may be

connected in series with the capacitive element). A variable capacitor circuit may bridge the gap. The switching inductor circuit, the tunable matching circuit, and the variable capacitor serve as antenna tuning
5 circuitry that can be used to allow the antenna to resonate at different frequency bands.

A wireless device formed using this arrangement may be operable in first and second modes. In the first mode, the switchable inductor circuit may be turned to
10 enable the antenna of the wireless device to operable in a first low-band region and a high-band region. In the second mode, the switchable inductor circuit may be turned off to enable the antenna of the wireless device to operate in a second low-band region and the high-band
15 region. The first and second low-band regions may or may not overlap in frequency.

The tunable matching circuit may be configured to provide desired sub-band coverage within a selected band region. The variable capacitor circuit may be
20 adjusted to fine tune the frequency characteristic of the loop antenna.

Further features of the invention, its nature and various advantages will be more apparent from the accompanying drawings and the following detailed
25 description of the preferred embodiments.

Brief Description of the Drawings

FIG. 1 is a perspective view of an illustrative electronic device with wireless communications circuitry
30 in accordance with an embodiment of the present invention.

FIG. 2 is a schematic diagram of an illustrative electronic device with wireless communications circuitry in accordance with an embodiment of the present invention.

FIG. 3 is a cross-sectional end view of an illustrative electronic device with wireless communications circuitry in accordance with an embodiment of the present invention.

5 FIG. 4 is a diagram of an illustrative antenna in accordance with an embodiment of the present invention.

FIG. 5 is a schematic diagram of an illustrative series-fed loop antenna that may be used in an electronic device in accordance with an embodiment of the present
10 invention.

FIG. 6 is a graph showing how an electronic device antenna may be configured to exhibit coverage in multiple communications bands in accordance with an embodiment of the present invention.

15 FIG. 7 is a schematic diagram of an illustrative parallel-fed loop antenna that may be used in an electronic device in accordance with an embodiment of the present invention.

FIG. 8 is a diagram of an illustrative parallel-feed loop antenna with an inductance interposed in the loop in accordance with an embodiment of the present
20 invention.

FIG. 9 is a diagram of an illustrative parallel-fed loop antenna having an inductive transmission line structure in accordance with an embodiment of the present
25 invention.

FIG. 10 is a diagram of an illustrative parallel-fed loop antenna with an inductive transmission line structure and a series-connected capacitive element in accordance with an embodiment of the present invention.
30

FIG. 11 is a Smith chart illustrating the performance of various electronic device loop antennas in accordance with embodiments of the present invention.

FIG. 12 is plot showing trade-offs between antenna gain and antenna bandwidth for a given antenna volume.

FIG. 13 is a diagram of an illustrative
5 parallel-fed loop antenna with tunable antenna circuitry in accordance with an embodiment of the present invention.

FIG. 14 is a circuit diagram of an illustrative tunable matching circuit of the type that may be used in connection with the antenna of FIG. 13 in accordance with
10 an embodiment of the present invention.

FIG. 15 is a circuit diagram of an illustrative switchable inductor circuit of the type that may be used in connection with the antenna of FIG. 13 in accordance with an embodiment of the present invention.

15 FIG. 16 is a circuit diagram of an illustrative variable capacitor circuit of the type that may be used in connection with the antenna of FIG. 13 in accordance with an embodiment of the present invention.

FIG. 17 is a plot showing how the low band
20 portions of the antenna of FIG. 13 may be used to cover multiple communications bands of interest using tunable antenna circuitry in accordance with an embodiment of the present invention.

25 Detailed Description

Electronic devices may be provided with wireless communications circuitry. The wireless communications circuitry may be used to support wireless communications in multiple wireless communications bands. The wireless
30 communications circuitry may include one or more antennas.

The antennas can include loop antennas. Conductive structures for a loop antenna may, if desired, be formed from conductive electronic device structures. The conductive electronic device structures may include

conductive housing structures. The housing structures may include a conductive bezel. Gap structures may be formed in the conductive bezel. The antenna may be parallel-fed using a configuration that helps to minimize sensitivity
5 of the antenna to contact with a user's hand or other external object.

Any suitable electronic devices may be provided with wireless circuitry that includes loop antenna structures. As an example, loop antenna structures may be
10 used in electronic devices such as desktop computers, game consoles, routers, laptop computers, etc. With one suitable configuration, loop antenna structures are provided in relatively compact electronic devices in which interior space is relatively valuable such as portable
15 electronic devices.

An illustrative portable electronic device in accordance with an embodiment of the present invention is shown in FIG. 1. Portable electronic devices such as illustrative portable electronic device 10 may be laptop
20 computers or small portable computers such as ultraportable computers, netbook computers, and tablet computers. Portable electronic devices may also be somewhat smaller devices. Examples of smaller portable electronic devices include wrist-watch devices, pendant
25 devices, headphone and earpiece devices, and other wearable and miniature devices. With one suitable arrangement, the portable electronic devices are handheld electronic devices such as cellular telephones.

Space is at a premium in portable electronic
30 devices. Conductive structures are also typically present, which can make efficient antenna operation challenging. For example, conductive housing structures may be present around some or all of the periphery of a portable electronic device housing.

In portable electronic device housing arrangements such as these, it may be particularly advantageous to use loop-type antenna designs that cover communications bands of interest. The use of portable
5 devices such as handheld devices is therefore sometimes described herein as an example, although any suitable electronic device may be provided with loop antenna structures, if desired.

Handheld devices may be, for example, cellular
10 telephones, media players with wireless communications capabilities, handheld computers (also sometimes called personal digital assistants), remote controllers, global positioning system (GPS) devices, and handheld gaming devices. Handheld devices and other portable devices may,
15 if desired, include the functionality of multiple conventional devices. Examples of multi-functional devices include cellular telephones that include media player functionality, gaming devices that include wireless communications capabilities, cellular telephones that
20 include game and email functions, and handheld devices that receive email, support mobile telephone calls, and support web browsing. These are merely illustrative examples. Device 10 of FIG. 1 may be any suitable portable or handheld electronic device.

25 Device 10 includes housing 12 and includes at least one antenna for handling wireless communications. Housing 12, which is sometimes referred to as a case, may be formed of any suitable materials including, plastic, glass, ceramics, composites, metal, or other suitable
30 materials, or a combination of these materials. In some situations, parts of housing 12 may be formed from dielectric or other low-conductivity material, so that the operation of conductive antenna elements that are located

within housing 12 is not disrupted. In other situations, housing 12 may be formed from metal elements.

Device 10 may, if desired, have a display such as display 14. Display 14 may, for example, be a touch
5 screen that incorporates capacitive touch electrodes. Display 14 may include image pixels formed from light-emitting diodes (LEDs), organic LEDs (OLEDs), plasma cells, electronic ink elements, liquid crystal display (LCD) components, or other suitable image pixel
10 structures. A cover glass member may cover the surface of display 14. Buttons such as button 19 may pass through openings in the cover glass.

Housing 12 may include sidewall structures such as sidewall structures 16. Structures 16 may be
15 implemented using conductive materials. For example, structures 16 may be implemented using a conductive ring member that substantially surrounds the rectangular periphery of display 14. Structures 16 may be formed from a metal such as stainless steel, aluminum, or other
20 suitable materials. One, two, or more than two separate structures may be used in forming structures 16. Structures 16 may serve as a bezel that holds display 14 to the front (top) face of device 10. Structures 16 are therefore sometimes referred to herein as bezel structures
25 16 or bezel 16. Bezel 16 runs around the rectangular periphery of device 10 and display 14.

Bezel 16 may have a thickness (dimension TT) of about 0.1 mm to 3 mm (as an example). The sidewall portions of bezel 16 may be substantially vertical
30 (parallel to vertical axis V). Parallel to axis V, bezel 16 may have a dimension TZ of about 1 mm to 2 cm (as an example). The aspect ratio R of bezel 16 (i.e., the of TZ to TT) is typically more than 1 (i.e., R may be greater

than or equal to 1, greater than or equal to 2, greater than or equal to 4, greater than or equal to 10, etc.).

It is not necessary for bezel 16 to have a uniform cross-section. For example, the top portion of bezel 16 may, if desired, have an inwardly protruding lip that helps hold display 14 in place. If desired, the bottom portion of bezel 16 may also have an enlarged lip (e.g., in the plane of the rear surface of device 10). In the example of FIG. 1, bezel 16 has substantially straight vertical sidewalls. This is merely illustrative. The sidewalls of bezel 16 may be curved or may have any other suitable shape.

Display 14 includes conductive structures such as an array of capacitive electrodes, conductive lines for addressing pixel elements, driver circuits, etc. These conductive structures tend to block radio-frequency signals. It may therefore be desirable to form some or all of the rear planar surface of device from a dielectric material such as plastic.

Portions of bezel 16 may be provided with gap structures. For example, bezel 16 may be provided with one or more gaps such as gap 18, as shown in FIG. 1. Gap 18 lies along the periphery of the housing of device 10 and display 12 and is therefore sometimes referred to as a peripheral gap. Gap 18 divides bezel 16 (i.e., there is generally no conductive portion of bezel 16 in gap 18).

As shown in FIG. 1, gap 18 may be filled with dielectric. For example, gap 18 may be filled with air. To help provide device 10 with a smooth uninterrupted appearance and to ensure that bezel 16 is aesthetically appealing, gap 18 may be filled with a solid (non-air) dielectric such as plastic. Bezel 16 and gaps such as gap 18 (and its associated plastic filler structure) may form part of one or more antennas in device 10. For example,

portions of bezel 16 and gaps such as gap 18 may, in conjunction with internal conductive structures, form one or more loop antennas. The internal conductive structures may include printed circuit board structures, frame
5 members or other support structures, or other suitable conductive structures.

In a typical scenario, device 10 may have upper and lower antennas (as an example). An upper antenna may, for example, be formed at the upper end of device 10 in
10 region 22. A lower antenna may, for example, be formed at the lower end of device 10 in region 20.

The lower antenna may, for example, be formed partly from the portions of bezel 16 in the vicinity of gap 18.

15 Antennas in device 10 may be used to support any communications bands of interest. For example, device 10 may include antenna structures for supporting local area network communications, voice and data cellular telephone communications, global positioning system (GPS)
20 communications, Bluetooth[®] communications, etc. As an example, the lower antenna in region 20 of device 10 may be used in handling voice and data communications in one or more cellular telephone bands.

A schematic diagram of an illustrative
25 electronic device is shown in FIG. 2. Device 10 of FIG. 2 may be a portable computer such as a portable tablet computer, a mobile telephone, a mobile telephone with media player capabilities, a handheld computer, a remote control, a game player, a global positioning system (GPS)
30 device, a combination of such devices, or any other suitable portable electronic device.

As shown in FIG. 2, handheld device 10 may include storage and processing circuitry 28. Storage and processing circuitry 28 may include storage such as hard

disk drive storage, nonvolatile memory (e.g., flash memory or other electrically-programmable-read-only memory configured to form a solid state drive), volatile memory (e.g., static or dynamic random-access-memory), etc.

5 Processing circuitry in storage and processing circuitry 28 may be used to control the operation of device 10. This processing circuitry may be based on one or more microprocessors, microcontrollers, digital signal processors, applications specific integrated circuits,
10 etc.

Storage and processing circuitry 28 may be used to run software on device 10, such as internet browsing applications, voice-over-internet-protocol (VOIP) telephone call applications, email applications, media
15 playback applications, operating system functions, etc. To support interactions with external equipment, storage and processing circuitry 28 may be used in implementing communications protocols. Communications protocols that may be implemented using storage and processing circuitry
20 28 include internet protocols, wireless local area network protocols (e.g., IEEE 802.11 protocols -- sometimes referred to as WiFi®), protocols for other short-range wireless communications links such as the Bluetooth® protocol, cellular telephone protocols, etc.

25 Input-output circuitry 30 may be used to allow data to be supplied to device 10 and to allow data to be provided from device 10 to external devices. Input-output devices 32 such as touch screens and other user input interface are examples of input-output circuitry 32.
30 Input-output devices 32 may also include user input-output devices such as buttons, joysticks, click wheels, scrolling wheels, touch pads, key pads, keyboards, microphones, cameras, etc. A user can control the operation of device 10 by supplying commands through such

user input devices. Display and audio devices such as display 14 (FIG. 1) and other components that present visual information and status data may be included in devices 32. Display and audio components in input-output devices 32 may also include audio equipment such as speakers and other devices for creating sound. If desired, input-output devices 32 may contain audio-video interface equipment such as jacks and other connectors for external headphones and monitors.

Wireless communications circuitry 34 may include radio-frequency (RF) transceiver circuitry formed from one or more integrated circuits, power amplifier circuitry, low-noise input amplifiers, passive RF components, one or more antennas, and other circuitry for handling RF wireless signals. Wireless signals can also be sent using light (e.g., using infrared communications). Wireless communications circuitry 34 may include radio-frequency transceiver circuits for handling multiple radio-frequency communications bands. Examples of cellular telephone standards that may be supported by wireless circuitry 34 and device 10 include: the Global System for Mobile Communications (GSM) "2G" cellular telephone standard, the Evolution-Data Optimized (EVDO) cellular telephone standard, the "3G" Universal Mobile Telecommunications System (UMTS) cellular telephone standard, the "3G" Code Division Multiple Access 2000 (CDMA 2000) cellular telephone standard, and the 3GPP Long Term Evolution (LTE) cellular telephone standard. Other cellular telephone standards may be used if desired. These cellular telephone standards are merely illustrative.

Wireless communications circuitry 34 can include circuitry for other short-range and long-range wireless links if desired. For example, wireless communications circuitry 34 may include global positioning system (GPS)

receiver equipment, wireless circuitry for receiving radio and television signals, paging circuits, etc. In WiFi® and Bluetooth® links and other short-range wireless links, wireless signals are typically used to convey data over
5 tens or hundreds of feet. In cellular telephone links and other long-range links, wireless signals are typically used to convey data over thousands of feet or miles.

Wireless communications circuitry 34 may include antennas 40. Antennas 40 may be formed using any suitable
10 antenna types. For example, antennas 40 may include antennas with resonating elements that are formed from loop antenna structure, patch antenna structures, inverted-F antenna structures, slot antenna structures, planar inverted-F antenna structures, helical antenna
15 structures, hybrids of these designs, etc. Different types of antennas may be used for different bands and combinations of bands. For example, one type of antenna may be used in forming a local wireless link antenna and another type of antenna may be used in forming a remote
20 wireless link.

With one suitable arrangement, which is sometimes described herein as an example, the lower antenna in device 10 (i.e., an antenna 40 located in region 20 of device 10 of FIG. 1) may be formed using a
25 loop-type antenna design. When a user holds device 10, the user's fingers may contact the exterior of device 10. For example, the user may touch device 10 in region 20. To ensure that antenna performance is not overly sensitive to the presence or absence of a user's touch or contact by
30 other external objects, the loop-type antenna may be fed using an arrangement that does not overly concentrate electric fields in the vicinity of gap 18.

A cross-sectional side view of device 10 of FIG. 1 taken along line 24-24 in FIG. 1 and viewed in direction

26 is shown in FIG. 3. As shown in FIG. 3, display 14 may be mounted to the front surface of device 10 using bezel 16. Housing 12 may include sidewalls formed from bezel 16 and one or more rear walls formed from structures such as planar rear housing structure 42. Structure 42 may be formed from a dielectric such as plastic or other suitable materials. Snaps, clips, screws, adhesive, and other structures may be used in attaching bezel 16 to display 14 and rear housing wall structure 42.

Device 10 may contain printed circuit boards such as printed circuit board 46. Printed circuit board 46 and the other printed circuit boards in device 10 may be formed from rigid printed circuit board material (e.g., fiberglass-filled epoxy) or flexible sheets of material such as polymers. Flexible printed circuit boards ("flex circuits") may, for example, be formed from flexible sheets of polyimide.

Printed circuit board 46 may contain interconnects such as interconnects 48. Interconnects 48 may be formed from conductive traces (e.g., traces of gold-plated copper or other metals). Connectors such as connector 50 may be connected to interconnects 48 using solder or conductive adhesive (as examples). Integrated circuits, discrete components such as resistors, capacitors, and inductors, and other electronic components may be mounted to printed circuit board 46.

Antenna 40 may have antenna feed terminals. For example, antenna 40 may have a positive antenna feed terminal such as positive antenna feed terminal 58 and a ground antenna feed terminal such as ground antenna feed terminal 54. In the illustrative arrangement of FIG. 3, a transmission line path such as coaxial cable 52 may be coupled between the antenna feed formed from terminals 58 and 54 and transceiver circuitry in components 44 via

connector 50 and interconnects 48. Components 44 may include one or more integrated circuits that implement the transceiver circuits 36 and 38 of FIG. 2. Connector 50 may be, for example, a coaxial cable connector that is
5 connected to printed circuit board 46. Cable 52 may be a coaxial cable or other transmission line. Terminal 58 may be coupled to coaxial cable center connector 56. Terminal 54 may be connected to a ground conductor in cable 52 (e.g., a conductive outer braid conductor). Other
10 arrangements may be used for coupling transceivers in device 10 to antenna 40 if desired. The arrangement of FIG. 3 is merely illustrative.

As the cross-sectional view of FIG. 3 makes clear, the sidewalls of housing 12 that are formed by
15 bezel 16 may be relatively tall. At the same time, the amount of area that is available to form an antenna in region 20 at the lower end of device 10 may be limited, particularly in a compact device. The compact size that is desired for forming the antenna may make it difficult
20 to form a slot-type antenna shape of sufficient size to resonant in desired communications bands. The shape of bezel 16 may tend to reduce the efficiency of conventional planar inverted-F antennas. Challenges such as these may, if desired, be addressed using a loop-type design for
25 antenna 40.

Consider, as an example, the antenna arrangement of FIG. 4. As shown in FIG. 4, antenna 40 may be formed in region 20 of device 10. Region 20 may be located at the lower end of device 10, as described in connection
30 with FIG. 1. Conductive region 68, which may sometimes be referred to as a ground plane or ground plane element, may be formed from one or more conductive structures (e.g., planar conductive traces on printed circuit board 46, internal structural members in device 10, electrical

components 44 on board 46, radio-frequency shielding cans mounted on board 46, etc.). Conductive region 68 in region 66 is sometimes referred to as forming a "ground region" for antenna 40. Conductive structures 70 of FIG. 4 may be formed by bezel 16. Regions 70 are sometimes referred to as ground plane extensions. Gap 18 may be formed in this conductive bezel portion (as shown in FIG. 1).

Ground plane extensions 70 (i.e., portions of bezel 16) and the portions of region 68 that lie along edge 76 of ground region 68 form a conductive loop around opening 72. Opening 72 may be formed from air, plastics and other solid dielectrics. If desired, the outline of opening 72 may be curved, may have more than four straight segments, and/or may be defined by the outlines of conductive components. The rectangular shape of dielectric region 72 in FIG. 4 is merely illustrative.

The conductive structures of FIG. 4 may, if desired, be fed by coupling radio-frequency transceiver 60 across ground antenna feed terminal 62 and positive antenna feed terminal 64. As shown in FIG. 4, in this type of arrangement, the feed for antenna 40 is not located in the vicinity of gap 18 (i.e., feed terminals 62 and 64 are located to the left of laterally centered dividing line 74 of opening 72, whereas gap 18 is located to the right of dividing line 74 along the right-hand side of device 10). While this type of arrangement may be satisfactory in some situations, antenna feed arrangements that locate the antenna feed terminals at the locations of terminals 62 and 64 of FIG. 4 tend to accentuate the electric field strength of the radio-frequency antenna signals in the vicinity of gap 18. If a user happens to place an external object such as finger 80 into the vicinity of gap 18 by moving finger 80 in direction 78

(e.g., when grasping device 10 in the user's hand), the presence of the user's finger may disrupt the operation of antenna 40.

To ensure that antenna 40 is not overly
5 sensitive to touch (i.e., to desensitize antenna 40 to touch events involving the hand of the user of device 10 and other external objects), antenna 40 may be fed using antenna feed terminals located in the vicinity of gap 18 (e.g., where shown by positive antenna feed terminal 58
10 and ground antenna feed terminal 54 in the FIG. 4 example). When the antenna feed is located to the right of line 74 and, more particularly, when the antenna feed is located close to gap 18, the electric fields that are produced at gap 18 tend to be reduced. This helps
15 minimize the sensitivity of antenna 40 to the presence of the user's hand, ensuring satisfactory operation regardless of whether or not an external object is in contact with device 10 in the vicinity of gap 18.

In the arrangement of FIG. 4, antenna 40 is
20 being series fed. A schematic diagram of a series-fed loop antenna of the type shown in FIG. 4 is shown in FIG. 5. As shown in FIG. 5, series-fed loop antenna 82 may have a loop-shaped conductive path such as loop 84. A transmission line composed of positive transmission line
25 conductor 86 and ground transmission line conductor 88 may be coupled to antenna feed terminals 58 and 54, respectively.

It may be challenging to effectively use a series-fed feed arrangement of the type shown in FIG. 5 to
30 feed a multi-band loop antenna. For example, it may be desired to operate a loop antenna in a lower frequency band that covers the GSM sub-bands at 850 MHz and 900 MHz and a higher frequency band that covers the GSM sub-bands at 1800 MHz and 1900 MHz and the data sub-band at 2100 MHz.

This type of arrangement may be considered to be a dual band arrangement (e.g., 850/900 for the first band and 1800/1900/2100 for the second band) or may be considered to have five bands (850, 900, 1800, 1900, and 2100). In multi-band arrangements such as these, series-fed antennas such as loop antenna 82 of FIG. 5 may exhibit substantially better impedance matching in the high-frequency communications band than in the low-frequency communications band.

A standing-wave-ratio (SWR) versus frequency plot that illustrates this effect is shown in FIG. 6. As shown in FIG. 6, SWR plot 90 may exhibit a satisfactory resonant peak (peak 94) at high-band frequency f_2 (e.g., to cover the sub-bands at 1800 MHz, 1900 MHz, and 2100 MHz). SWR plot 90 may, however, exhibit a relatively poor performance in the low-frequency band centered at frequency f_1 when antenna 40 is series fed. For example, SWR plot 90 for a series-fed loop antenna 82 of FIG. 5 may be characterized by weak resonant peak 96. As this example demonstrates, series-fed loop antennas may provide satisfactory impedance matching to transmission line 52 (FIG. 3) in a higher frequency band at f_2 , but may not provide satisfactory impedance matching to transmission line 52 (FIG. 3) in lower frequency band f_1 .

A more satisfactory level of performance (illustrated by low-band resonant peak 92) may be obtained using a parallel-fed arrangement with appropriate impedance matching features.

An illustrative parallel-fed loop antenna is shown schematically in FIG. 7. As shown in FIG. 7, parallel-fed loop antenna 90 may have a loop of conductor such as loop 92. Loop 92 in the FIG. 7 example is shown as being circular. This is merely illustrative. Loop 92 may have other shapes if desired (e.g., rectangular

shapes, shapes with both curved and straight sides, shapes with irregular borders, etc.). Transmission line TL may include positive signal conductor 94 and ground signal conductor 96. Paths 94 and 96 may be contained in coaxial
5 cables, micro-strip transmission lines on flex circuits and rigid printed circuit boards, etc. Transmission line TL may be coupled to the feed of antenna 90 using positive antenna feed terminal 58 and ground antenna feed terminal 54. Electrical element 98 may bridge terminals 58 and 54,
10 thereby "closing" the loop formed by path 92. When the loop is closed in this way, element 98 is interposed in the conductive path that forms loop 92. The impedance of parallel-fed loop antennas such as loop antenna 90 of FIG. 7 may be adjusted by proper selection of the element 98
15 and, if desired, other circuits (e.g., capacitors or other elements interposed in one of the feed lines such as line 94 or line 96).

Element 98 may be formed from one or more electrical components. Components that may be used as all
20 or part of element 98 include resistors, inductors, and capacitors. Desired resistances, inductances, and capacitances for element 98 may be formed using integrated circuits, using discrete components and/or using dielectric and conductive structures that are not part of
25 a discrete component or an integrated circuit. For example, a resistance can be formed using thin lines of a resistive metal alloy, capacitance can be formed by spacing two conductive pads close to each other that are separated by a dielectric, and an inductance can be formed
30 by creating a conductive path on a printed circuit board. These types of structures may be referred to as resistors, capacitors, and/or inductors or may be referred to as capacitive antenna feed structures, resistive antenna feed structures and/or inductive antenna feed structures.

An illustrative configuration for antenna 40 in which component 98 of the schematic diagram of FIG. 7 has been implemented using an inductor is shown in FIG. 8. As shown in FIG. 8, loop 92 (FIG. 7) may be implemented using
5 conductive regions 70 and the conductive portions of region 68 that run along edge 76 of opening 72. Antenna 40 of FIG. 8 may be fed using positive antenna feed terminal 58 and ground antenna feed terminal 54. Terminals 54 and 58 may be located in the vicinity of gap
10 18 to reduce electric field concentrations in gap 18 and thereby reduce the sensitivity of antenna 40 to touch events.

The presence of inductor 98 may at least partly help match the impedance of transmission line 52 to
15 antenna 40. If desired, inductor 98 may be formed using a discrete component such as a surface mount technology (SMT) inductor. The inductance of inductor 98 may also be implemented using an arrangement of the type shown in FIG. 9. With the configuration of FIG. 9, the loop conductor
20 of parallel-fed loop antenna 40 may have an inductive segment SG that runs parallel to ground plane edge GE. Segment SG may be, for example, a conductive trace on a printed circuit board or other conductive member. A dielectric opening DL (e.g., an air-filled or plastic-
25 filled opening) may separate edge portion GE of ground 68 from segment SG of conductive loop portion 70. Segment SG may have a length L. Segment SG and associated ground GE form a transmission line with an associated inductance (i.e., segment SG and ground GE form inductor 98). The
30 inductance of inductor 98 is connected in parallel with feed terminals 54 and 58 and therefore forms a parallel inductive tuning element of the type shown in FIG. 8. Because inductive element 98 of FIG. 9 is formed using a transmission line structure, inductive element 98 of FIG.

9 may introduce fewer losses into antenna 40 than arrangements in which a discrete inductor is used to bridge the feed terminals. For example, transmission-line inductive element 98 may preserve high-band performance (illustrated as satisfactory resonant peak 94 of FIG. 6), whereas a discrete inductor might reduce high-band performance.

Capacitive tuning may also be used to improve impedance matching for antenna 40. For example, capacitor 100 of FIG. 10 may be connected in series with center conductor 56 of coaxial cable 52 or other suitable arrangements can be used to introduce a series capacitance into the antenna feed. As shown in FIG. 10, capacitor 100 may be interposed in coaxial cable center conductor 56 or other conductive structures that are interposed between the end of transmission line 52 and positive antenna feed terminal 58. Capacitor 100 may be formed by one or more discrete components (e.g., SMT components), by one or more capacitive structures (e.g., overlapping printed circuit board traces that are separated by a dielectric, etc.), lateral gaps between conductive traces on printed circuit boards or other substrates, etc.

The conductive loop for loop antenna 40 of FIG. 10 is formed by conductive structures 70 and the conductive portions of ground conductive structures 66 along edge 76. Loop currents can also pass through other portions of ground plane 68, as illustrated by current paths 102. Positive antenna feed terminal 58 is connected to one end of the loop path and ground antenna feed terminal 54 is connected to the other end of the loop path. Inductor 98 bridges terminals 54 and 58 of antenna 40 of FIG. 10, so antenna 40 forms a parallel-fed loop antenna with a bridging inductance (and a series capacitance from capacitor 100).

During operation of antenna 40, a variety of current paths 102 of different lengths may be formed through ground plane 68. This may help to broaden the frequency response of antenna 40 in bands of interest.

5 The presence of tuning elements such as parallel inductance 98 and series capacitance 100 may help to form an efficient impedance matching circuit for antenna 40 that allows antenna 40 to operate efficiently at both high and low bands (e.g., so that antenna 40 exhibits high-band
10 resonance peak 94 of FIG. 6 and low-band resonance peak 92 of FIG. 6).

A simplified Smith chart showing the possible impact of tuning elements such as inductor 98 and capacitor 100 of FIG. 10 on parallel-fed loop antenna 40
15 is shown in FIG. 11. Point Y in the center of chart 104 represents the impedance of transmission line 52 (e.g., a 50 ohm coaxial cable impedance to which antenna 40 is to be matched). Configurations in which the impedance of antenna 40 is close to point Y in both the low and high
20 bands will exhibit satisfactory operation.

With parallel-fed antenna 40 of FIG. 10, high-band matching is relatively insensitive to the presence or absence of inductive element 98 and capacitor 100. However, these components may significantly affect low
25 band impedance. Consider, as an example, an antenna configuration without either inductor 98 or capacitor 100 (i.e., a parallel-fed loop antenna of the type shown in FIG. 4). In this type of configuration, the low band (e.g., the band at frequency f1 of FIG. 6) may be
30 characterized by an impedance represented by point X1 on chart 104. When an inductor such as parallel inductance 98 of FIG. 9 is added to the antenna, the impedance of the antenna in the low band may be characterized by point X2 of chart 104. When a capacitor such as capacitor 100 is

added to the antenna, the antenna may be configured as shown in FIG. 10. In this type of configuration, the impedance of the antenna 40 may be characterized by point X3 of chart 104.

5 At point X3, antenna 40 is well matched to the impedance of cable 50 in both the high band (frequencies centered about frequency f2 in FIG. 6) and the low band (frequencies centered about frequency f1 in FIG. 6). This may allow antenna 40 to support desired communications
10 bands of interest. For example, this matching arrangement may allow antennas such as antenna 40 of FIG. 10 to operate in bands such as the communications bands at 850 MHz and 900 MHz (collectively forming the low band region at frequency f1) and the communications bands at 1800 MHz,
15 1900 MHz, and 2100 MHz (collectively forming the high band region at frequency f2).

Moreover, the placement of point X3 helps ensure that detuning due to touch events is minimized. When a user touches housing 12 of device 10 in the vicinity of
20 antenna 40 or when other external objects are brought into close proximity with antenna 40, these external objects affect the impedance of the antenna. In particular, these external objects may tend to introduce a capacitive impedance contribution to the antenna impedance. The
25 impact of this type of contribution to the antenna impedance tends to move the impedance of the antenna from point X3 to point X4, as illustrated by line 106 of chart 104 in FIG. 11. Because of the original location of point X3, point X4 is not too far from optimum point Y. As a
30 result, antenna 40 may exhibit satisfactory operation under a variety of conditions (e.g., when device 10 is being touched, when device 10 is not being touched, etc.).

Although the diagram of FIG. 11 represents impedances as points for various antenna configurations,

the antenna impedances are typically represented by a collection of points (e.g., a curved line segment on chart 104) due to the frequency dependence of antenna impedance. The overall behavior of chart 104 is, however,

5 representative of the behavior of the antenna at the frequencies of interest. The use of curved line segments to represent frequency-dependent antenna impedances has been omitted from FIG. 11 to avoid over-complicating the drawing.

10 Antenna 40 of the type described in connection with FIG. 10 may be capable of supporting wireless communications in first and second radio-frequency bands (see, e.g., FIG. 6). For example, antenna 40 may be operable in a lower frequency band that covers the GSM
15 sub-bands at 850 MHz and 900 MHz and a higher frequency band that covers the GSM sub-bands at 1800 MHz and 1900 MHz and the data sub-band at 2100 MHz.

It may be desirable for device 10 to be able to support other wireless communications bands in addition to
20 the first and second bands. For example, it may be desirable for antenna 40 to be capable of operating in a higher frequency band that covers the GSM sub-bands at 1800 MHz and 1900 MHz and the data sub-band at 2100 MHz, a first lower frequency band that covers the GSM sub-bands
25 at 850 MHz and 900 MHz, and a second lower frequency band that covers the LTE band at 700 MHz, the GSM sub-bands at 710 MHz and 750 MHz, the UMTS sub-band at 700 MHz, and other desired wireless communications bands.

The band coverage of antenna 40 of the type
30 described in connection of FIG. 10 may be limited by the volume (e.g., the volume of the opening defined by conductive loop 70) of loop antenna 40. In general, for a loop antenna having a given volume, a higher band coverage

(or bandwidth) results in a decrease in gain (e.g., the product of maximum gain and bandwidth is constant).

FIG. 12 is a graph showing how antenna gain varies as a function of antenna bandwidth. Curve 200 represents a gain-bandwidth characteristic for a first loop antenna having a first volume, whereas curve 202 represents a gain-bandwidth characteristic for a second loop antenna having a second volume that is greater than the first volume. The first and second loop antennas may be antennas of the type described in connection with FIG. 10.

As shown in FIG. 12, the first loop antenna can provide bandwidth BW1 while exhibiting gain g_0 (point 204). In order to provide more bandwidth (i.e., bandwidth BW2) with the first loop antenna, the gain of the first loop antenna would be lowered to gain g_1 (point 205). One way of providing more band coverage is to increase the volume of the loop antenna. For example, the second loop antenna having a greater volume than the volume of the first loop antenna is capable of providing bandwidth BW2 while exhibiting g_0 (point 206). Increasing the volume of loop antennas, however, may not always be feasible if a small form factor is desired.

In another suitable arrangement, the wireless circuitry of device 10 may include tunable (configurable) antenna circuitry. The tunable antenna circuitry may allow antenna 40 to be operable in at least three wireless communications bands (as an example). The tunable antenna circuitry may include a switchable inductor circuit such as circuit 210, tunable matching network circuitry such as matching circuitry M1, a variable capacitor circuit such as circuit 212, and other suitable tunable circuits (see, e.g., FIG. 13).

As shown in FIG. 13, loop conductor 70 of parallel-fed loop antenna 40 may have a first inductive segment SG and a second inductive segment SG' that run parallel to ground plane edge GE. Segments SG and SG' may be, for example, conductive traces on a printed circuit board or other conductive member. Dielectric opening DL (e.g., an air-filled or plastic-filled opening) may separate edge portion GE of ground 68 from segment SG of conductive loop portion 70, whereas dielectric opening DL' may separate edge portion GE of ground 68 from segment SG' of conductive loop portion 70. Dielectric openings DL and DL' may have different shapes and sizes.

Segment SG and SG' may be connected through a portion 99 of conductor 70 that runs perpendicular to ground plane edge GE. Switchable inductor circuit (also referred to as tunable inductor circuit, configurable inductor circuit, or adjustable inductor circuit) 210 may be coupled between portion 99 and a corresponding terminal 101 on ground plane edge GE. When circuit 210 is switched into use (e.g., when circuit 210 is turned on), segment SG and associated ground GE form a first transmission line path with a first inductance (i.e., segment SG and ground GE form inductor 98). When circuit 210 is switched out of use (e.g., when circuit 210 is turned off), segment SG, portion 99, segment SG', and ground GE collective form a second transmission line path with a second inductance (i.e., segment SG' and ground GE form inductor 98' that is coupled in series with inductor 98). The second transmission line path may sometimes be referred to as being a fixed inductor, because the inductance of the second transmission line path is fixed when switchable inductor 210 is not in use. Switchable inductor 210 serves to shunt the second transmission line path so that

the first inductance value is lower than the second inductance value.

The dimensions of segments SG and SG' are selected so that the equivalent inductance values for the first and second inductances are equal to 18 nH and 20 nH, respectively (as an example). The first transmission line path (if circuit 210 is enabled) and the second transmission line path (if circuit 210 is disabled) are connected in parallel with feed terminals 54 and 58 and serve as parallel inductive tuning elements for antenna 40. The first and second transmission line path may therefore sometimes be referred to as a variable inductor. Because the first and second inductances are provided using transmission line structures, the first and second transmission line paths may preserve high-band performance (illustrated as satisfactory resonant peak 94 of FIG. 6), whereas discrete inductors might reduce high-band performance.

The presence of inductor 98 may at least partly help match the impedance of transmission line 52 to antenna 40 when circuit 210 is turned on, whereas the presence of the series-connected inductors 98 and 98' may partly help match the impedance of line 52 to antenna 40 when circuit 210 is turned off. If desired, inductors 98 and 98' may be formed using discrete components such as surface mount technology (SMT) inductors. Inductors 98 and 98' have inductance values that are carefully chosen to provide desired band coverage.

In another suitable embodiment, tunable matching network circuitry M1 may be coupled between the coaxial cable 52 and capacitor 100. For example, tunable circuitry M1 may have a first terminal 132 connected to the coaxial cable center conductor and a second terminal 122 connected to capacitor 100. Impedance matching

circuitry M1 may be formed using conductive structures with associated capacitance, resistance, and inductance values, and/or discrete components such as inductors, capacitors, and resistors that form circuits to match the
5 impedances of transceiver circuitry 38 and antenna 40.

Matching circuitry M1 may be fixed or adjustable. In this type of configuration, a control circuit such as antenna tuning circuit 220 may issue control signals such as signal SELECT on path 29 to
10 configure matching circuitry M1. When SELECT has a first value, matching circuitry M1 may be placed in a first configuration. When SELECT has a second value, matching circuitry M1 may be placed in a second configuration. The state of matching circuitry M1 may serve to tune antenna
15 40 so that desired communications bands are covered by antenna 40.

In another suitable embodiment, a variable capacitor circuit (sometimes referred to as a varactor circuit, a tunable capacitor circuit, an adjustable
20 capacitor circuit, etc.) 212 may be coupled between conductive bezel gap 18. Bezel gap 18 may, for example, have an intrinsic capacitance of 1 pF (e.g., an inherent capacitance value formed by the parallel conductive surfaces at gap 18). Component 212 may be, for example, a
25 continuously variable capacitor, a semi continuously adjustable capacitor that has two to four or more different capacitance values that can be coupled in parallel to the intrinsic capacitance. If desired, component 212 may be a continuously variable inductor or a
30 semi continuously adjustable inductor that has two to four or more different inductance values. The capacitance value of component 212 may serve to fine tune antenna 40 for operation at desired frequencies.

Illustrative tunable circuitry that may be used for implementing tunable matching circuitry M1 of FIG. 13 is shown in FIG. 14. As shown in FIG. 14, matching circuitry M1 may have switches such as switches 134 and 136. Switches 134 and 136 may have multiple positions (shown by the illustrative A and B positions in FIG. 14). When signal SELECT has a first value, switches 134 and 136 may be put in their A positions and matching circuit MA may be switched into use. When signal SELECT has a second value, switches 134 and 136 may be placed in their B positions (as shown in FIG. 14), so that matching circuit MB is connected between paths 132 and 122.

FIG. 15 shows one suitable circuit implementation of switchable inductor circuit 210. As shown in FIG. 15, circuit 210 includes a switch SW and inductive element 98' coupled in series. Switch SW may be implemented using a p-i-n diode, a gallium arsenide field-effect transistor (FET), a microelectromechanical systems (MEMS) switch, a metal-oxide-semiconductor field-effect transistor (MOSFET), a high-electron mobility transistor (HEMT), a pseudomorphic HEMT (PHEMT), a transistor formed on a silicon-on-insulator (SOI) substrate, etc.

Inductive element 98' may be formed from one or more electrical components. Components that may be used as all or part of element 98' include resistors, inductors, and capacitors. Desired resistances, inductances, and capacitances for element 98' may be formed using integrated circuits, using discrete components (e.g., a surface mount technology inductor) and/or using dielectric and conductive structures that are not part of a discrete component or an integrated circuit. For example, a resistance can be formed using thin lines of a resistive metal alloy, capacitance can be formed by spacing two conductive pads close to each other that are

separated by a dielectric, and an inductance can be formed by creating a conductive path (e.g., a transmission line) on a printed circuit board.

FIG. 16 shows how varactor circuit 212 may receive control voltage signal V_c from antenna tuning circuit 220. As shown in FIG. 16, varactor circuit 212 may have a first terminal connected to one end of bezel gap 18, a second terminal connected to another end of bezel gap 18, and a third terminal that receives control signal V_c . Antenna tuning circuit 220 may bias V_c to different voltage levels to adjust the capacitance of varactor 212. Varactor 212 may be formed from using integrated circuits, one or more discrete components (e.g., SMT components), etc.

By using antenna tuning schemes of the type described in connection with FIGS. 13-16, antenna 40 may be able to cover a wider range of communications frequencies than would otherwise be possible. FIG. 17 shows an illustrative SWR plot for antenna 40 of the type described in connection with FIG. 13. The solid line 90 corresponds to a first mode of antenna 40 when inductive circuit 220 is enabled. In this first mode, antenna 40 can operate in bands at a first low-band region at frequency f_1 (e.g., to cover the GSM bands at 850 MHz and 900 MHz) and in bands at a high-band region at frequency f_2 (e.g., to cover the GSM bands at 1800 MHz, 1900 MHz, and 2100 MHz).

The dotted line 90' corresponds to a second mode of antenna 40 when inductive circuit 220 is disabled. In this second mode, antenna 40 can operate in bands at a second low-band region at frequency f_1' (e.g., to cover the LTE band at 700 MHz and other bands of interest) while preserving coverage at the high-band region at frequency

f2. Tunable matching circuitry M1 may be configured to provide coverage at the desired sub-band.

Varactor circuit 212 may be used to fine tune antenna 40 prior to operation of device 10 or in real-time so that antenna 40 performs as desired under a variety of wireless traffic and environmental scenarios and to compensate for process, voltage, and temperature variations, and other sources of noise, interference, or variation.

10 In accordance with an embodiment, a parallel-fed loop antenna in an electronic device having a periphery is provide that includes: an antenna feed that includes first and second antenna feed terminals; a conductive loop coupled between the first and second antenna feed
15 terminals, where the conductive loop is formed at least partly from conductive structures disposed along the periphery; and a variable inductor that bridges the first and second antenna feed terminals.

In accordance with another embodiment, the
20 variable inductor includes a fixed inductor and a switchable inductor that are coupled in parallel between the first and second antenna feed terminals.

In accordance with another embodiment, the switchable inductor includes an inductor and a switch that
25 are connected in series between the first and second antenna feed terminals.

In accordance with another embodiment, the fixed inductor and the inductor includes inductive transmission line structures.

In accordance with another embodiment, the variable inductor is selectively configured to operate in a first mode in which the variable inductor exhibits a first inductance between the first and second antenna feed terminals and a second mode in which the variable inductor

exhibits a second inductance between the first and second antenna feed terminals, where the first inductance is different than the second inductance.

In accordance with another embodiment, where the conductive structures includes at least one gap, the parallel-fed loop antenna further includes a variable capacitor circuit that bridges the at least one gap.

In accordance with another embodiment, the electronic device further includes wireless transceiver circuitry and tunable impedance matching circuitry interposed between the transceiver circuitry and the antenna feeds.

In accordance with another embodiment, the electronic device further includes: wireless transceiver circuitry; and tunable impedance matching circuitry interposed between the transceiver circuitry and the antenna feeds.

In accordance with another embodiment, the parallel-fed loop antenna further includes: an antenna feed line that carries antenna signals between a transmission line and the first antenna feed terminal; and a capacitor interposed in the antenna feed line.

In accordance with an embodiment, a handheld electronic device is provided that includes: an antenna feed that includes first and second antenna feed terminals; a conductive loop coupled between the first and second antenna feed terminals; wireless transceiver circuitry; and tunable impedance matching circuitry interposed between the wireless transceiver circuitry and the antenna feed.

In accordance with another embodiment, the handheld electronic device further includes: a housing having a periphery; and a conductive structure that runs

along the periphery and that has at least one gap on the periphery.

In accordance with another embodiment, the handheld electronic device further includes: a variable capacitor circuit that bridges the at least one gap.

In accordance with another embodiment, the tunable impedance matching circuitry includes at least two impedance matching network circuits and switching circuitry that configures the tunable impedance matching circuitry to switch into use a selected one of the two impedance matching network circuits.

In accordance with another embodiment, the antenna includes a parallel-fed loop antenna.

In accordance with another embodiment, the electronic device further includes: a transmission line having positive and ground conductors, wherein the ground conductor is coupled to the second antenna feed terminal and wherein the positive conductor is coupled to the first antenna feed terminal; and a capacitor interposed in the positive conductor of the transmission line.

In accordance with another embodiment, the electronic device further includes: inductor circuitry that bridges the first and second antenna feed terminals.

In accordance with an embodiment, a wireless electronic device is provided that includes: a housing having a periphery; a conductive structure that runs along the periphery and that has at least one gap on the periphery; and an antenna formed at least partly from the conductive structure, wherein the antenna comprises antenna tuning circuitry that configures the antenna to operate in: a first operating mode in which the antenna is configured to operate in a first communications band and a second communications band that is higher in frequency than the first communications band; and a second operating

mode in which the antenna is configured to operate in a third communications band that is lower in frequency than the first communications band and the second communications band.

In accordance with another embodiment, the first communications band is centered at 900 MHz, the second communications band is centered at 1850 MHz, and the third communications band is centered at 700 MHz.

In accordance with another embodiment, the antenna tuning circuitry includes: variable capacitor circuitry that bridges the at least one gap.

In accordance with another embodiment, the antenna includes positive and negative feeds and the antenna tuning circuitry includes: a variable inductor that bridges the positive and negative antenna feed terminals.

In accordance with another embodiment, the antenna further includes an antenna feed and the antenna tuning circuitry includes tunable impedance matching circuitry having: radio transceiver circuitry, where the tunable impedance matching circuitry is interposed between the radio transceiver circuitry and the antenna feed.

The foregoing is merely illustrative of the principles of this invention and various modifications can be made by those skilled in the art without departing from the scope and spirit of the invention.

What is Claimed is:

1. A parallel-fed loop antenna in an electronic device having a periphery, comprising:
 - an antenna feed that includes first and second antenna feed terminals;
 - a conductive loop coupled between the first and second antenna feed terminals, wherein the conductive loop is formed at least partly from conductive structures disposed along the periphery; and
 - a variable inductor that bridges the first and second antenna feed terminals.
2. The parallel-fed loop antenna defined in claim 1, wherein the variable inductor comprises a fixed inductor and a switchable inductor that are coupled in parallel between the first and second antenna feed terminals.
3. The parallel-fed loop antenna defined in claim 2, wherein the switchable inductor comprises an inductor and a switch that are connected in series between the first and second antenna feed terminals.
4. The parallel-fed loop antenna defined in claim 3, wherein the fixed inductor and the inductor comprise inductive transmission line structures.
5. The parallel-fed loop antenna defined in claim 1, wherein the variable inductor is selectively configured to operate in a first mode in which the variable inductor exhibits a first inductance between the first and second antenna feed terminals and a second mode in which the variable inductor exhibits a second inductance between the first and second antenna feed

terminals and wherein the first inductance is different than the second inductance.

6. The parallel-fed loop antenna defined in claim 1, wherein the conductive structures comprise at least one gap, further comprising:

a variable capacitor circuit that bridges the at least one gap.

7. The parallel-fed loop antenna defined in claim 6, wherein the electronic device further comprises wireless transceiver circuitry and tunable impedance matching circuitry interposed between the transceiver circuitry and the antenna feeds.

8. The parallel-fed loop antenna defined in claim 1, wherein the electronic device further comprises:
wireless transceiver circuitry; and
tunable impedance matching circuitry
interposed between the transceiver circuitry and the antenna feeds.

9. The parallel-fed loop antenna defined in claim 1 further comprising:
an antenna feed line that carries antenna signals between a transmission line and the first antenna feed terminal; and
a capacitor interposed in the antenna feed line.

10. A handheld electronic device comprising:
an antenna feed that includes first and second antenna feed terminals;

a conductive loop coupled between the first and second antenna feed terminals;

wireless transceiver circuitry; and

tunable impedance matching circuitry interposed between the wireless transceiver circuitry and the antenna feed.

11. The handheld electronic device defined in claim 10, further comprising:

a housing having a periphery; and

a conductive structure that runs along the periphery and that has at least one gap on the periphery.

12. The handheld electronic device defined in claim 11, further comprising:

a variable capacitor circuit that bridges the at least one gap.

13. The handheld electronic device defined in claim 11, wherein the tunable impedance matching circuitry comprises at least two impedance matching network circuits and switching circuitry that configures the tunable impedance matching circuitry to switch into use a selected one of the two impedance matching network circuits.

14. The electronic device defined in claim 11, wherein the antenna comprises a parallel-fed loop antenna.

15. The electronic device defined in claim 11, further comprising:

a transmission line having positive and ground conductors, wherein the ground conductor is coupled to the second antenna feed terminal and wherein the

positive conductor is coupled to the first antenna feed terminal; and

a capacitor interposed in the positive conductor of the transmission line.

16. The electronic device defined in claim 11 further comprising:

inductor circuitry that bridges the first and second antenna feed terminals.

17. A wireless electronic device, comprising:

a housing having a periphery;

a conductive structure that runs along the periphery and that has at least one gap on the periphery; and

an antenna formed at least partly from the conductive structure, wherein the antenna comprises antenna tuning circuitry that configures the antenna to operate in:

a first operating mode in which the antenna is configured to operate in a first communications band and a second communications band that is higher in frequency than the first communications band; and

a second operating mode in which the antenna is configured to operate in a third communications band that is lower in frequency than the first communications band and the second communications band.

18. The wireless electronic device defined in claim 17, wherein the first communications band is centered at 900 MHz, wherein the second communications band is centered at 1850 MHz, and wherein the third communications band is centered at 700 MHz.

19. The wireless electronic device defined in claim 17, wherein the antenna tuning circuitry comprises:
variable capacitor circuitry that bridges the at least one gap.

20. The wireless electronic device defined in claim 17, wherein the antenna comprises positive and negative feeds and wherein the antenna tuning circuitry comprises:

a variable inductor that bridges the positive and negative antenna feed terminals.

21. The wireless electronic device defined in claim 17, wherein the antenna further comprises an antenna feed and wherein the antenna tuning circuitry comprises tunable impedance matching circuitry, further comprising:

radio transceiver circuitry, wherein the tunable impedance matching circuitry is interposed between the radio transceiver circuitry and the antenna feed.

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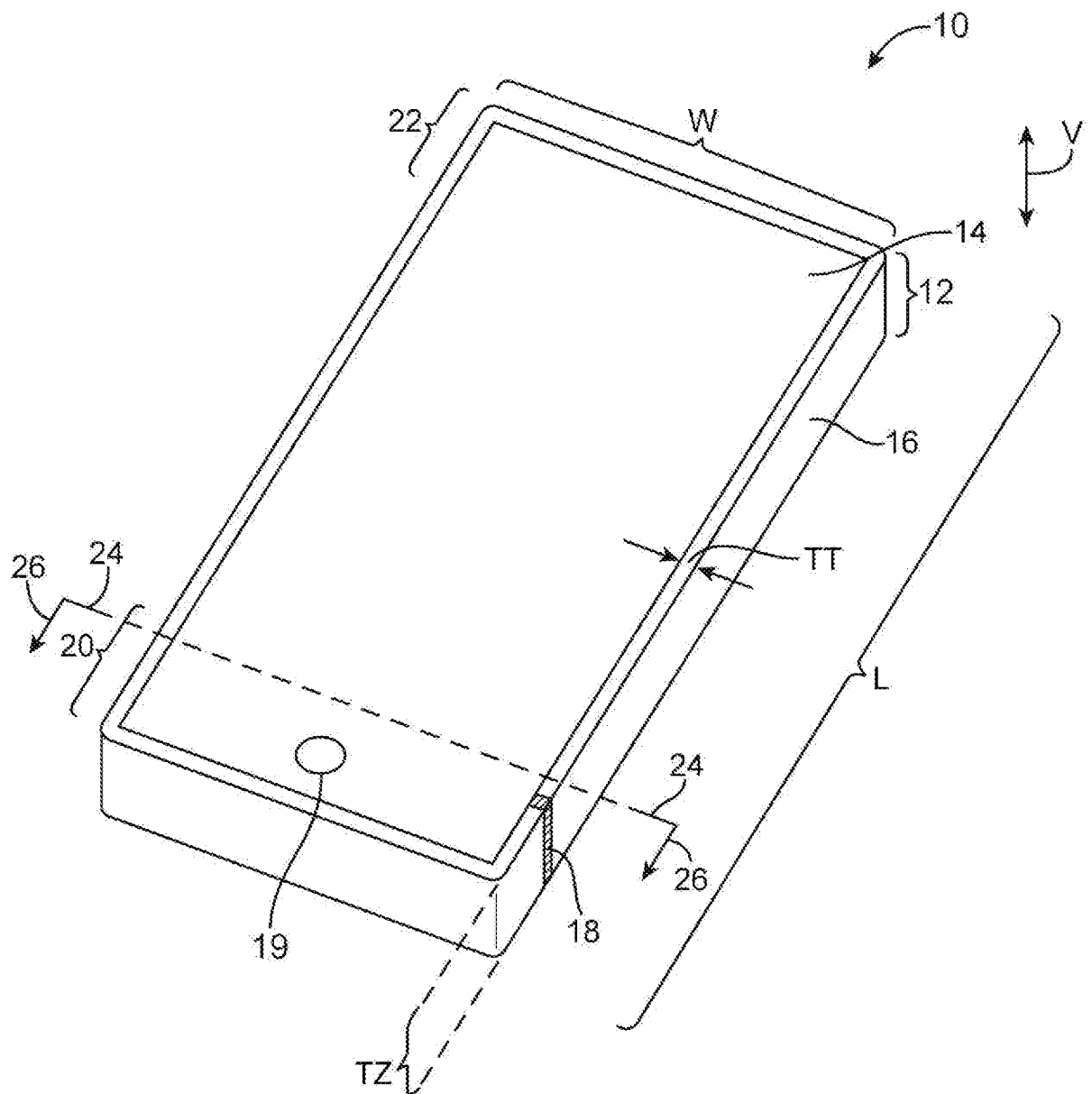


FIG. 1

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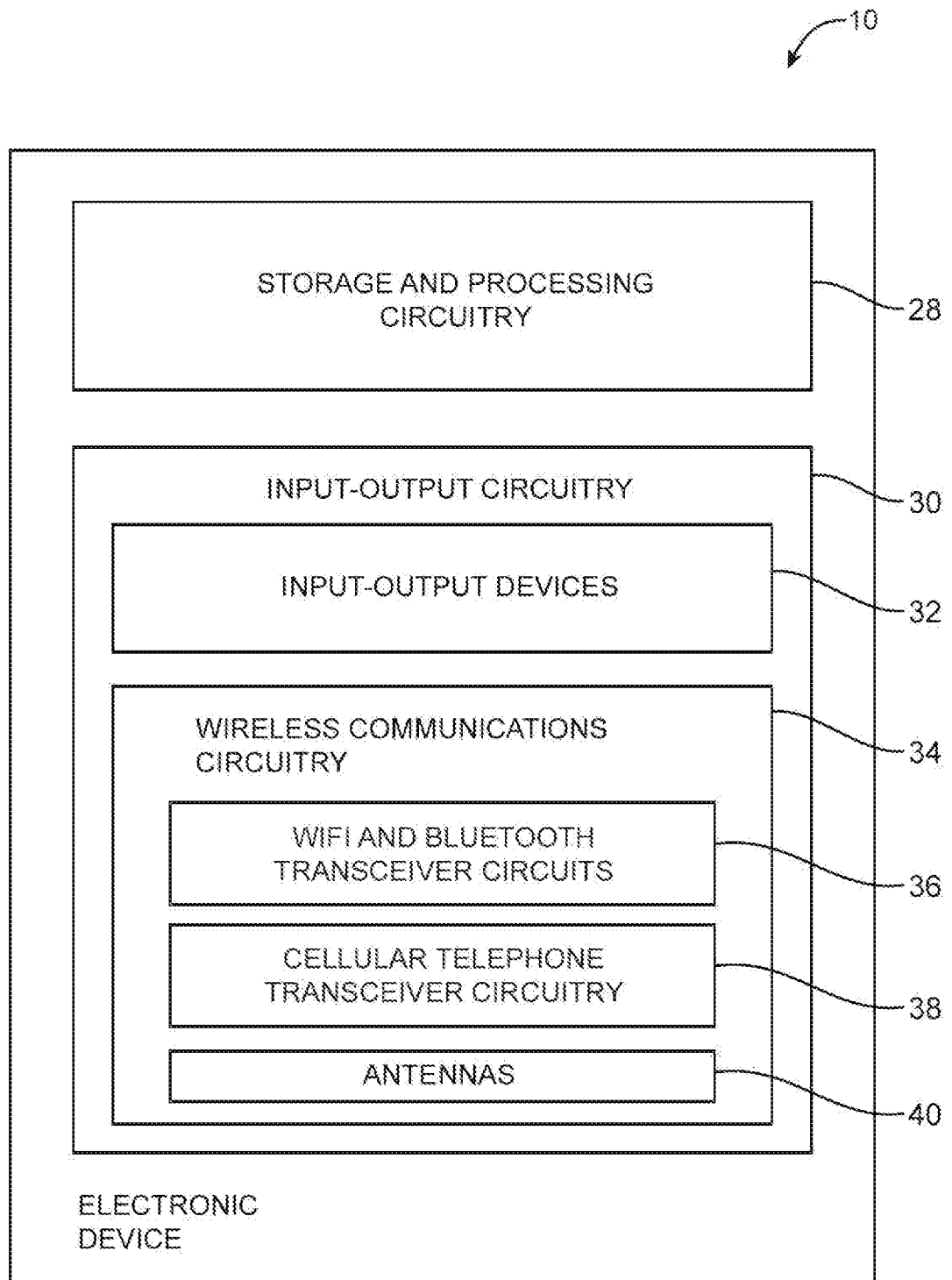


FIG. 2

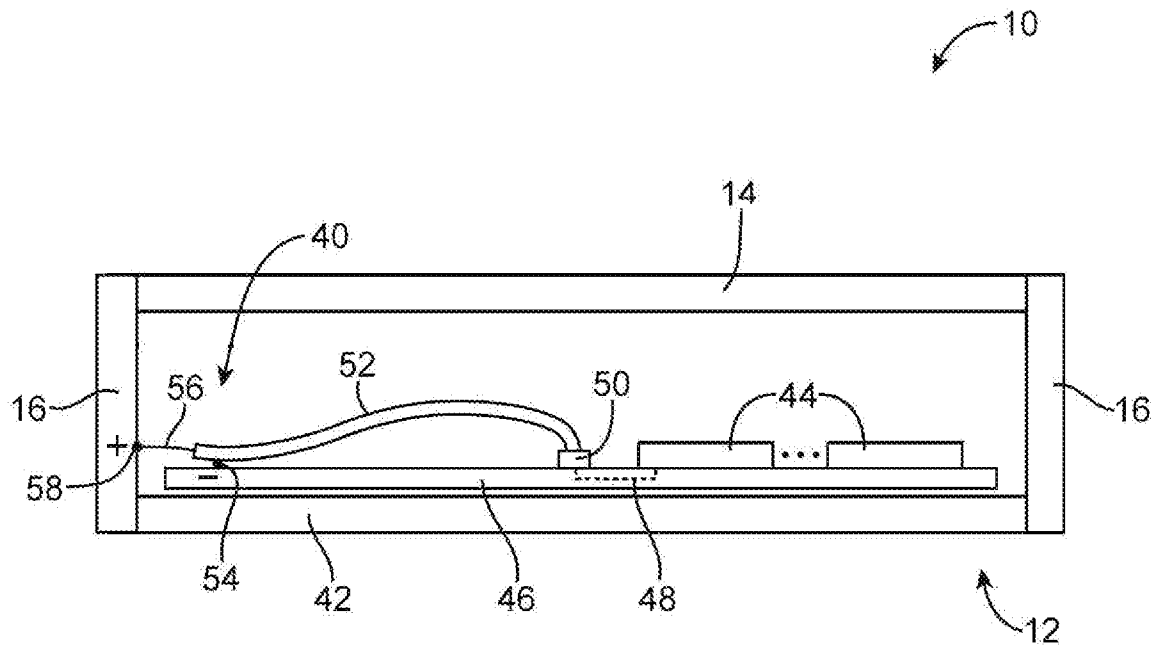


FIG. 3

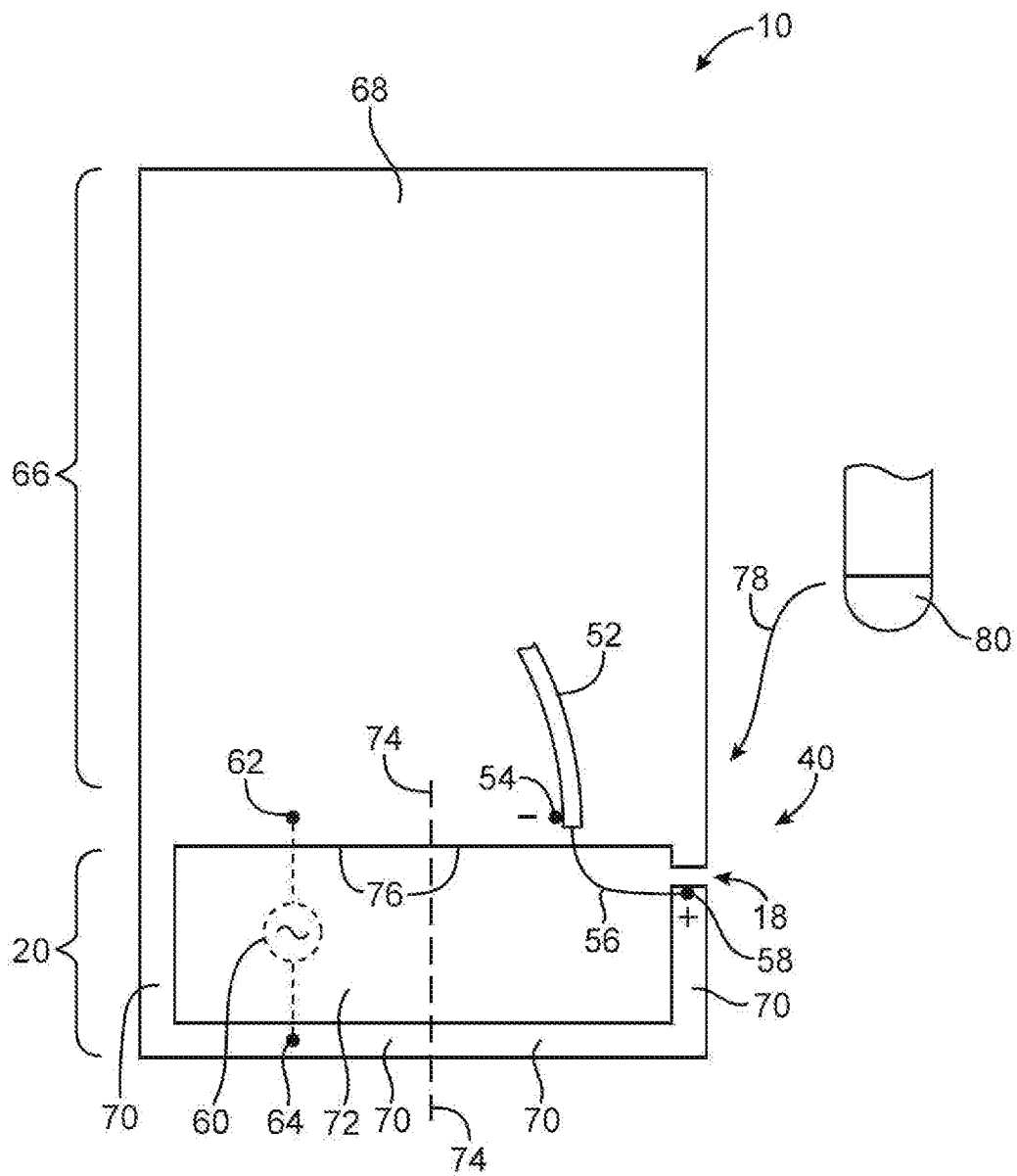


FIG. 4

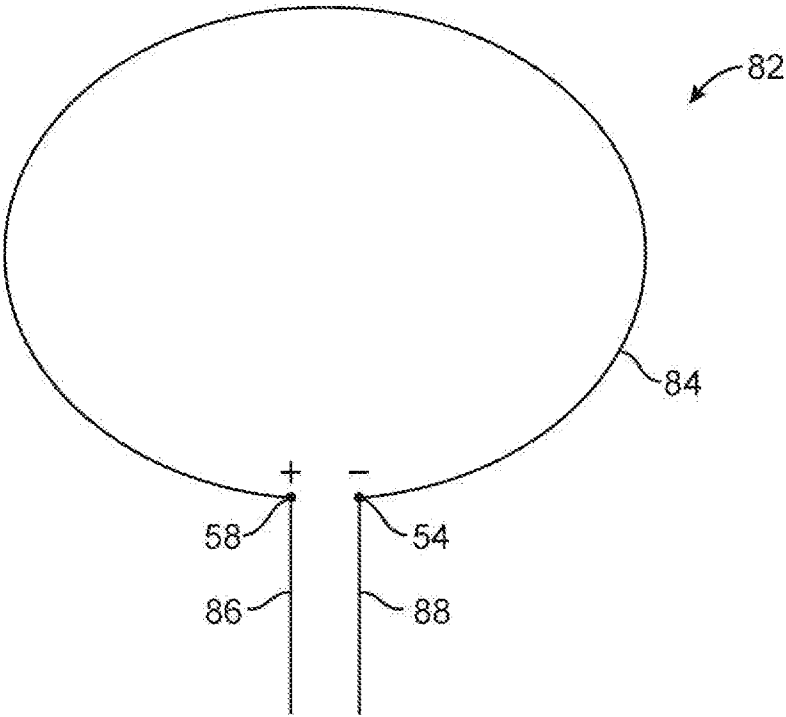


FIG. 5

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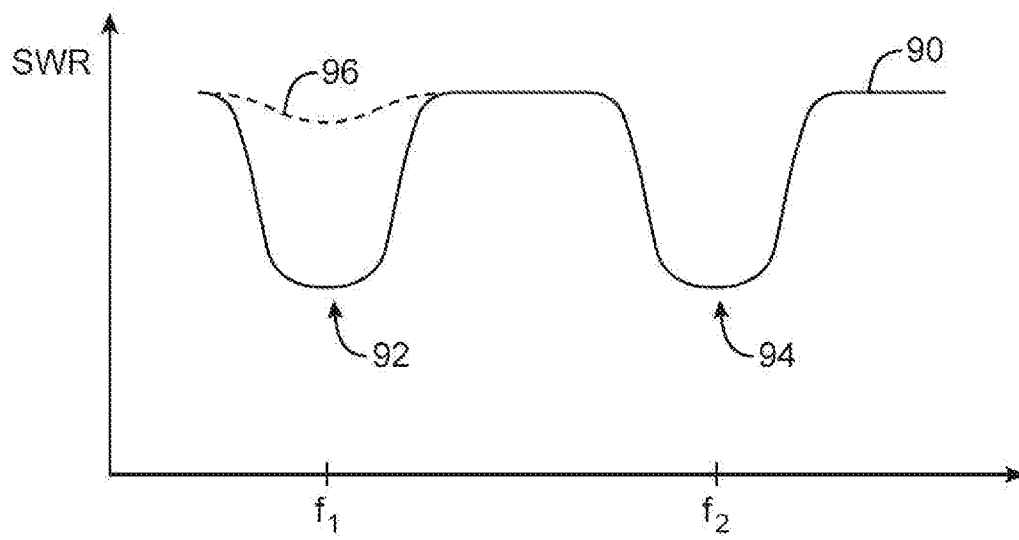


FIG. 6

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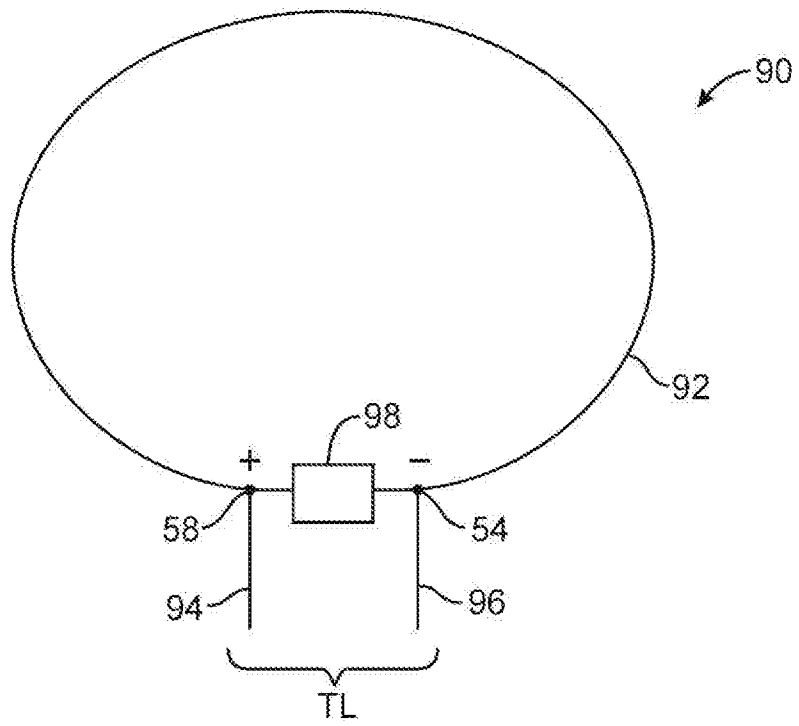


FIG. 7

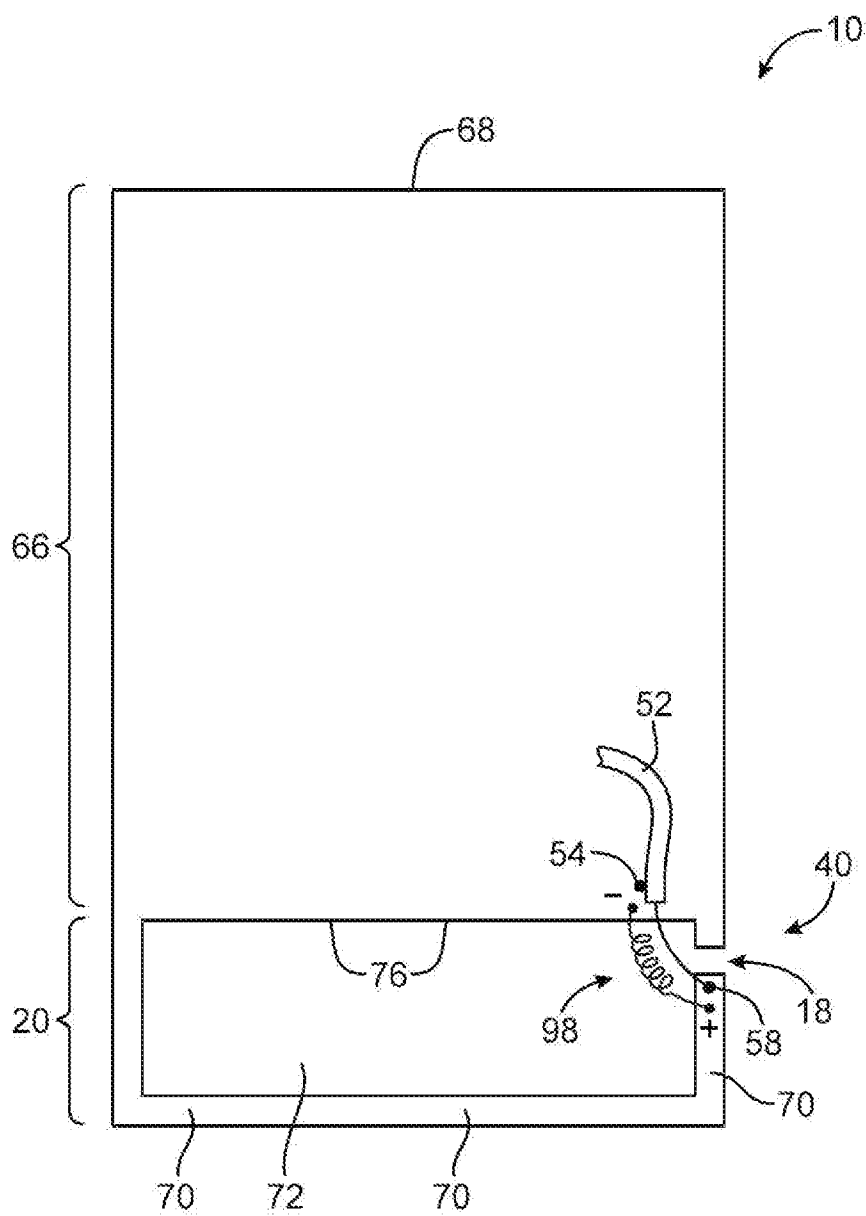


FIG. 8

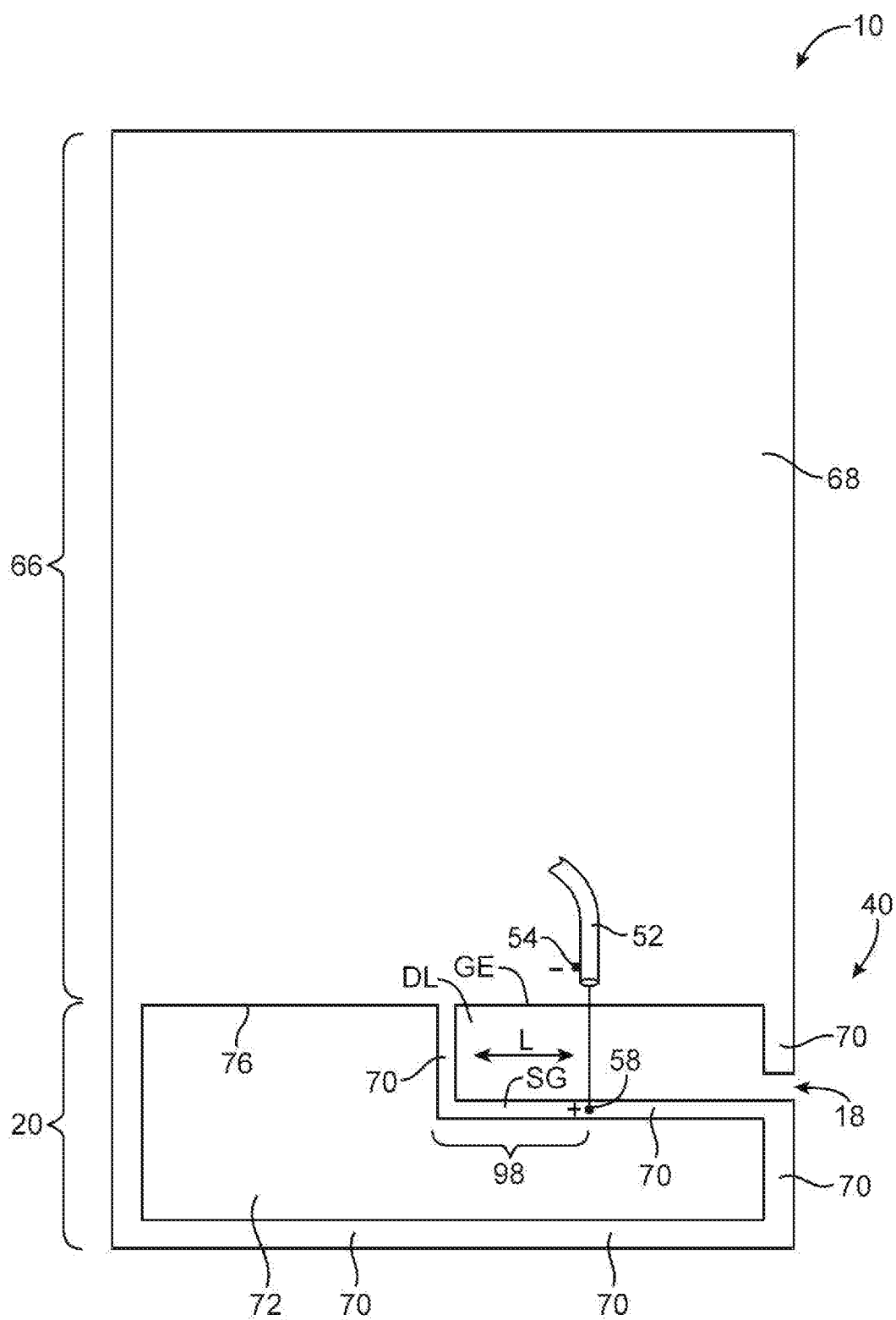


FIG. 9

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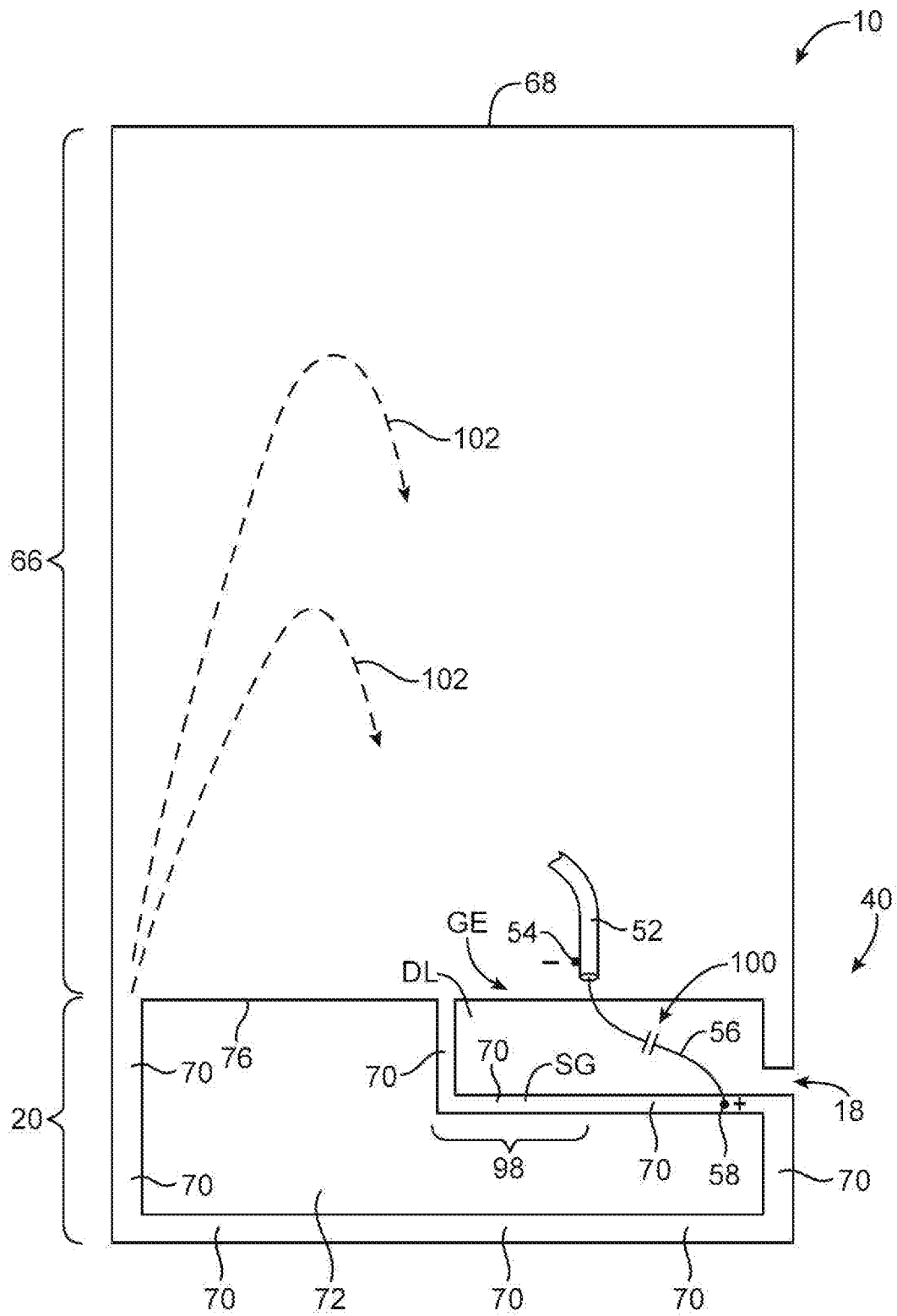


FIG. 10

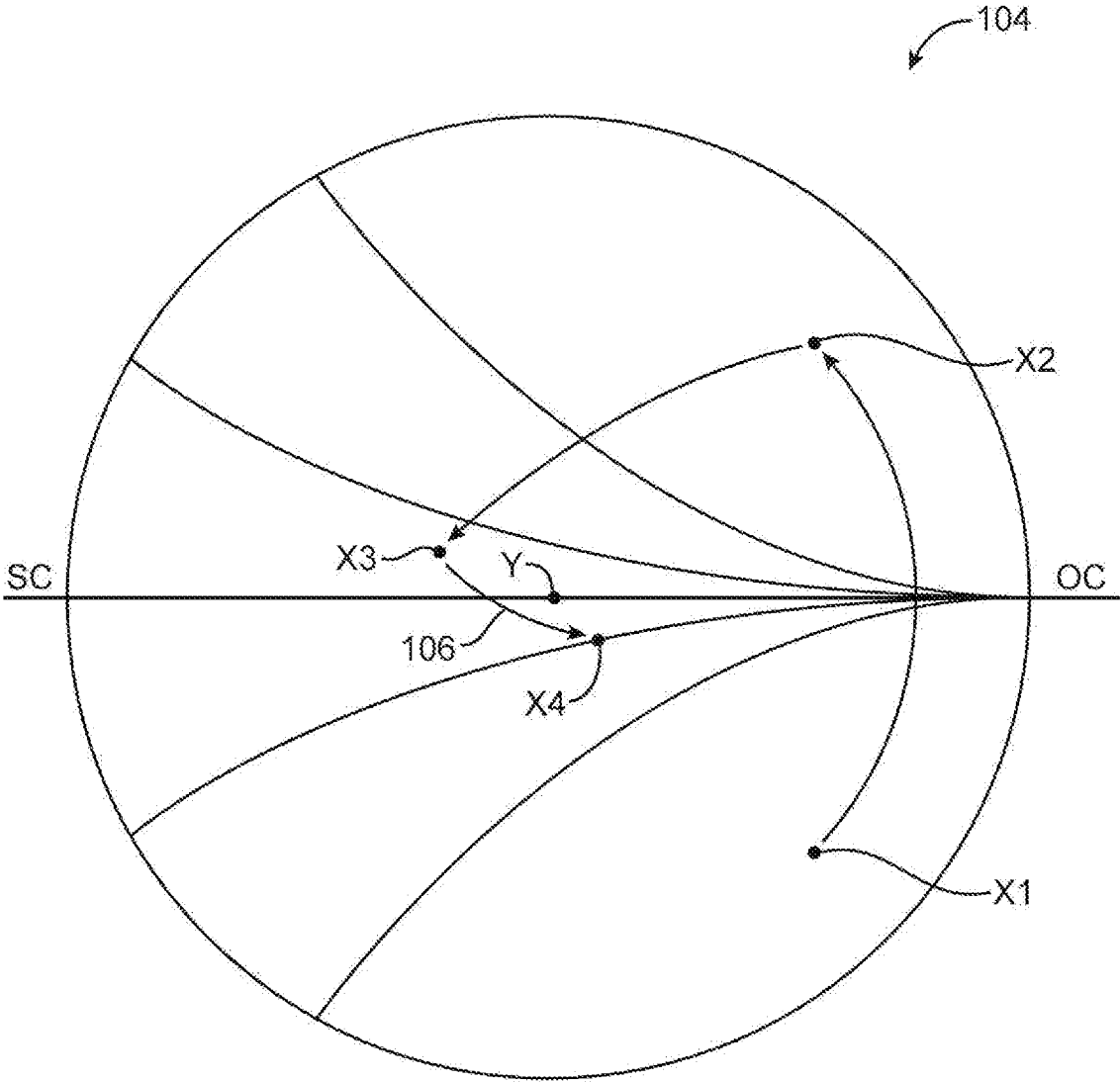


FIG. 11

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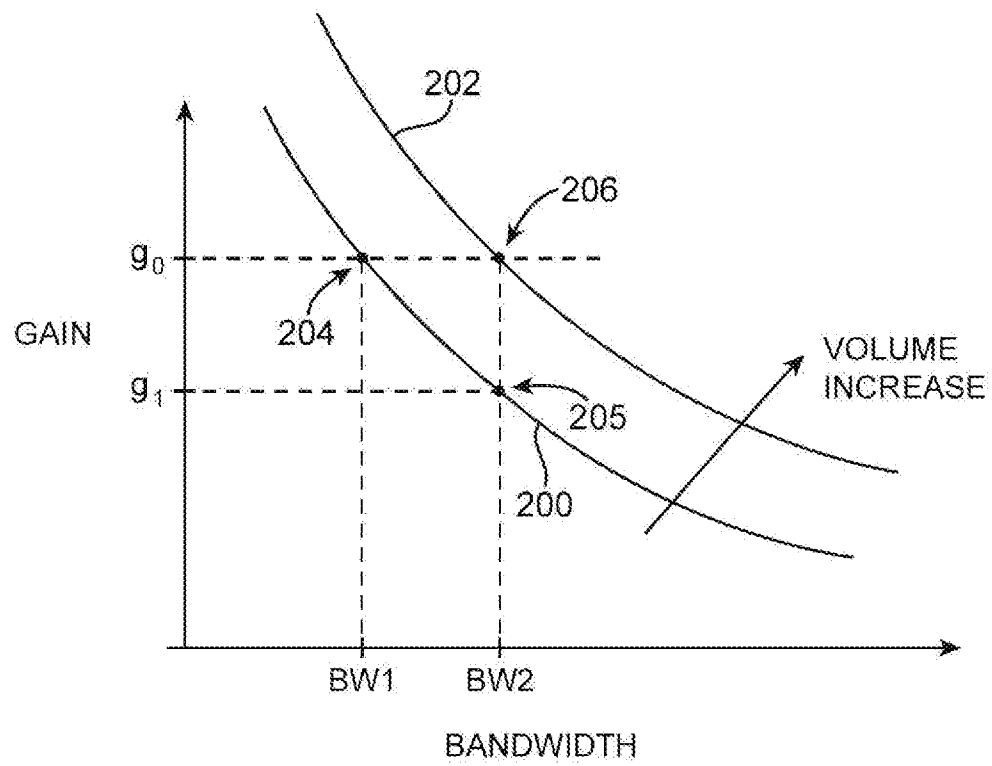


FIG. 12

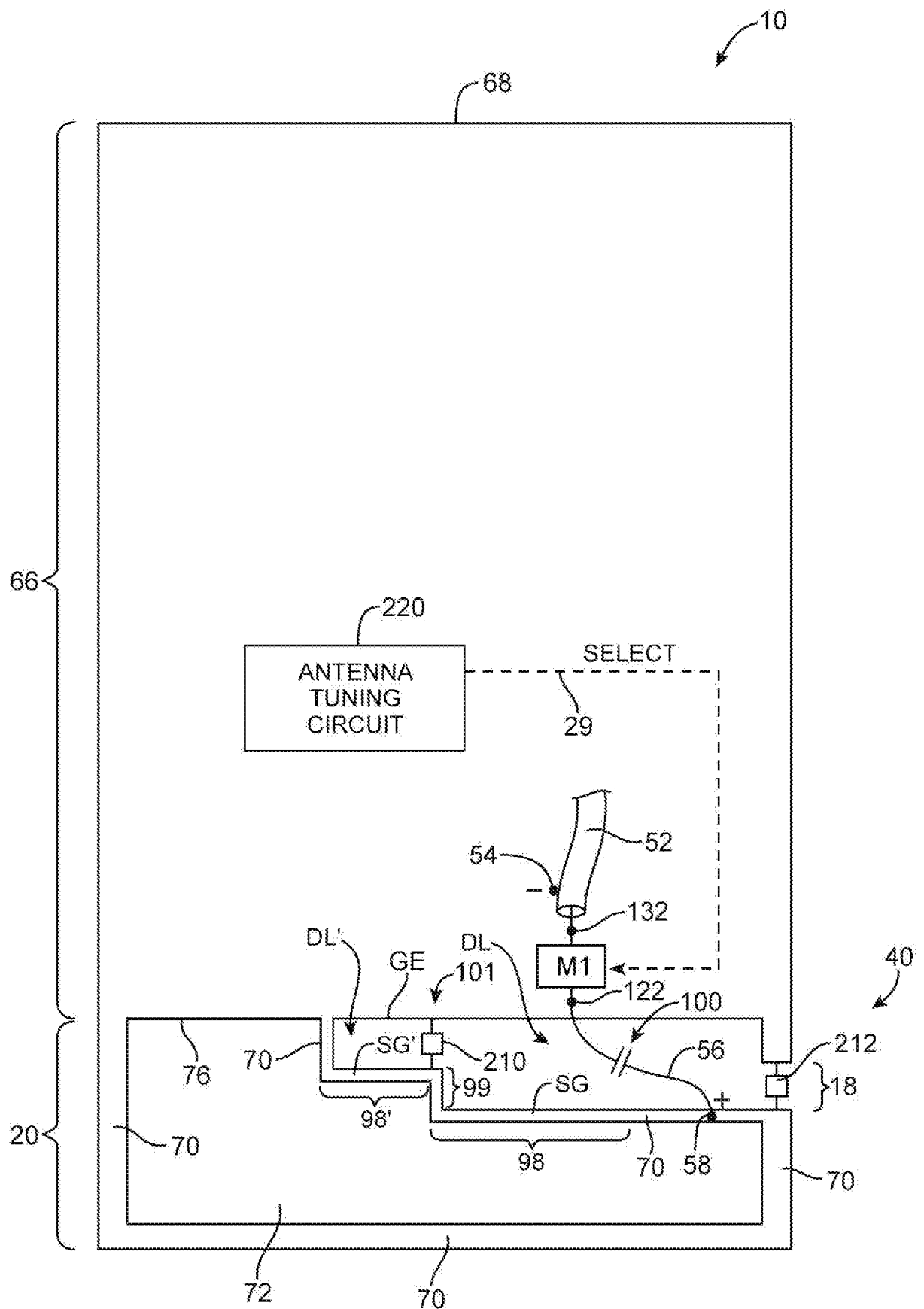


FIG. 13

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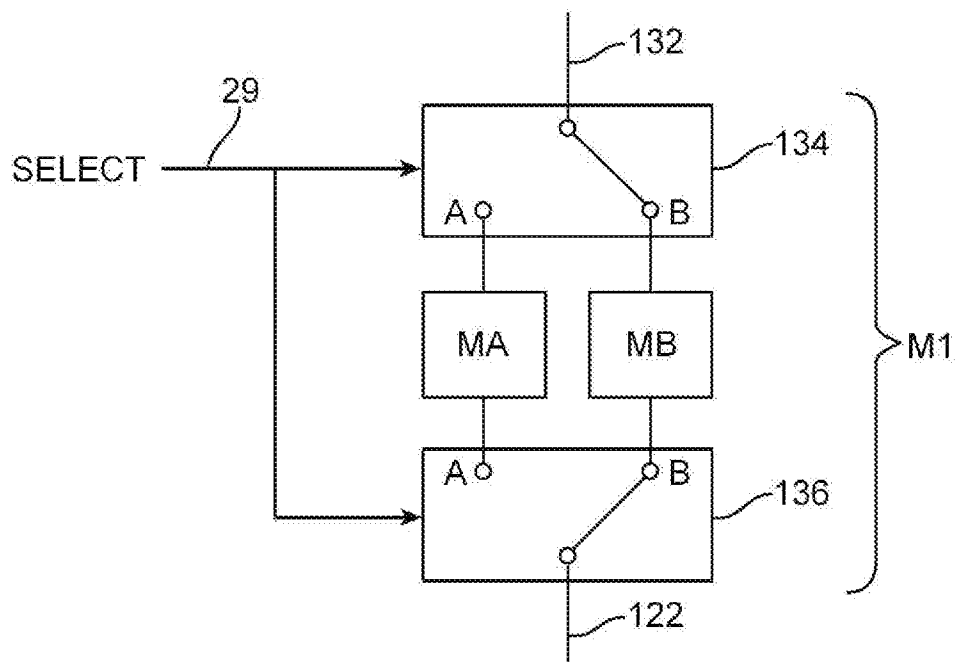


FIG. 14

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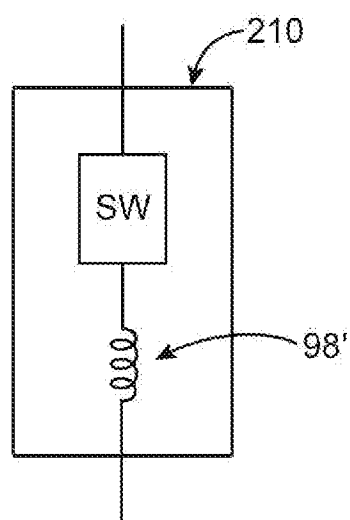


FIG. 15

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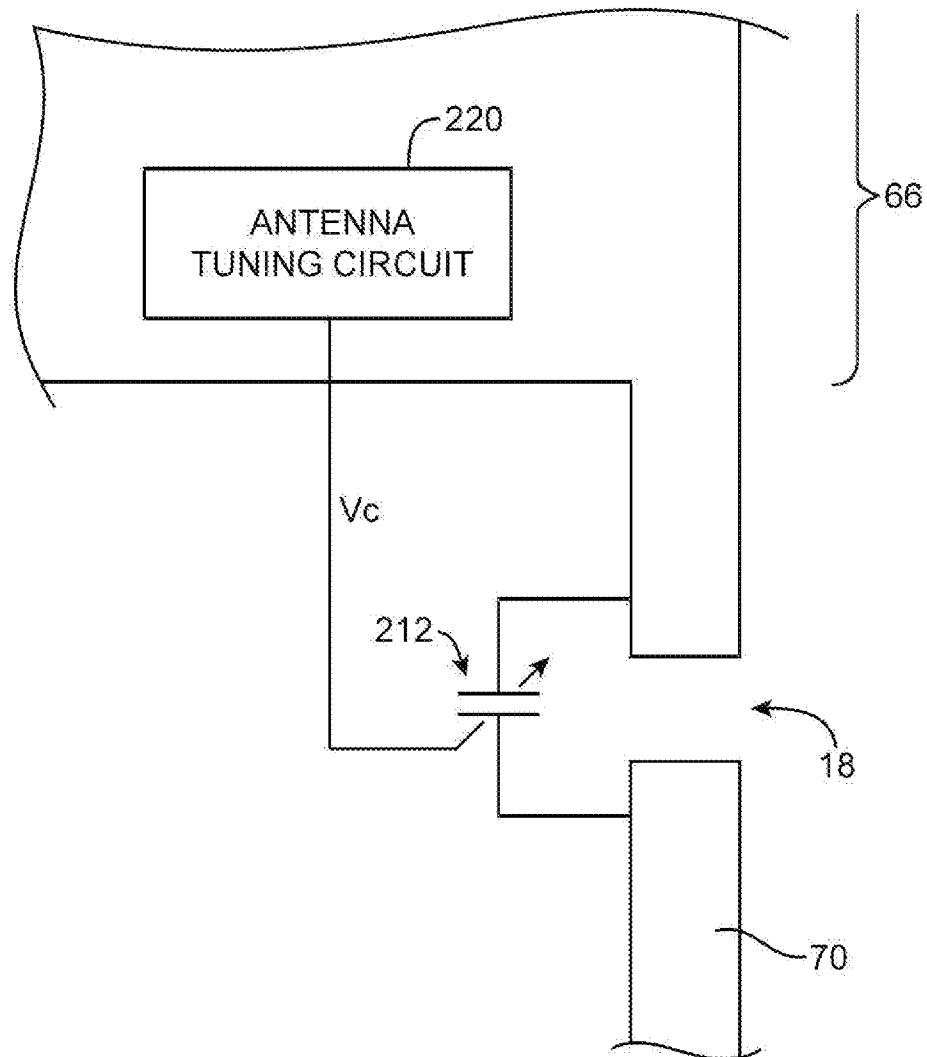


FIG. 16

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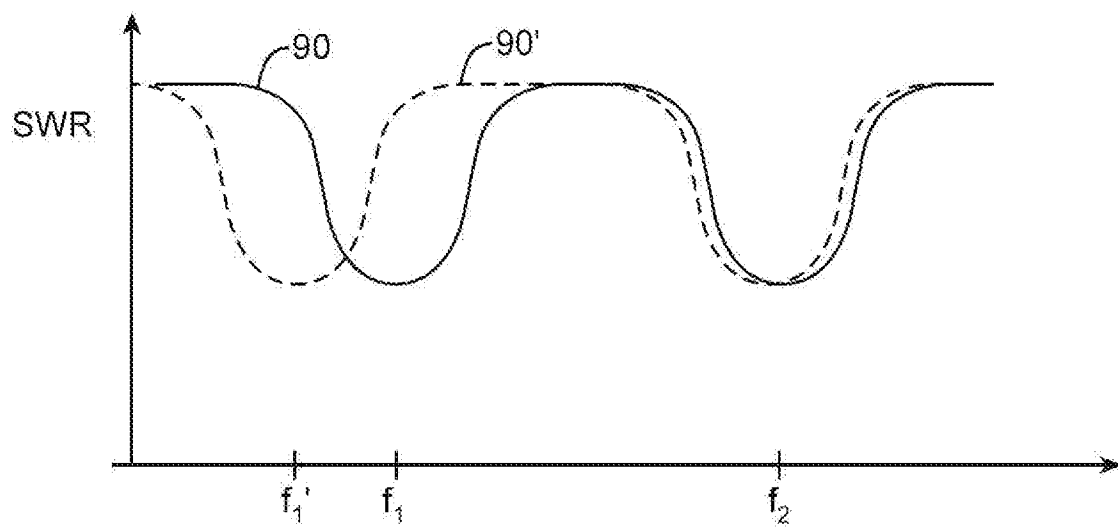


FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2012/025624

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H04B 1/38 (2012.01)

USPC - 455/90.2

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8) - H01Q 1/24, 1/50, 21/00; H04B 1/38 (2012.01)

USPC - 343/702, 850, 867; 455/90.2

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

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

Questel Orbit, Google Patent, ProQuest

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2011/0006953 A1 (CHIANG et al) 13 January 2011 (13.01.2011) entire document	1-21
Y	US 5,381,387 A (BLONDER et al) 10 January 1995 (10.01.1995) entire document	1-9, 14, 16
Y	US 2007/0146218 A1 (TURNER et al) 28 June 2007 (28.06.2007) entire document	2-5, 20
Y	US 7,671,693 B2 (BROBSTON et al) 02 March 2010 (02.03.2010) entire document	6-8, 10-16, 21
Y	US 2006/0055606 A1 (BOYLE) 16 March 2006 (16.03.2006) entire document	9, 15
Y	US 2008/0218291 A1 (ZHU et al) 11 September 2008 (11.09.2008) entire document	13
Y	US 2010/0214180 A1 (KROGERUS) 26 August 2010 (26.08.2010) entire document	17-21
Y	US 2009/0180403 A1 (TUDOSOIU) 16 July 2009 (16.07.2009) entire document	18
A	US 2010/0271271 A1 (WU) 28 October 2010 (28.10.2010) paragraphs 8-13	1-21

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

* Special categories of cited documents:

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

06 June 2012

Date of mailing of the international search report

14 JUN 2012

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-3201

Authorized officer:

Blaine R. Copenheaver

PCT Helpdesk: 571-272-4300

PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2012/025624

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

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

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

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

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

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

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

See extra sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☒ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2012/025624

Continuation of Box III.

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-16, drawn to an electronic device having a parallel-fed loop antenna which has first and second feed terminals; a conductive loop between the first and second terminals; a variable impedance bridging the feed terminals.

Group II, claims 17-21, drawn to a wireless electronic device having a housing; an antenna configured to operate in a first operating mode having two communications bands where the second band is of a higher frequency than the first; and a second operating mode having a third communications band that is higher in frequency than the first and second communications bands.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: a parallel-fed loop antenna which has first and second feed terminals; a conductive loop between the first and second terminals; a variable impedance bridging the feed terminals as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: an antenna configured to operate in a first operating mode having two communications bands where the second band is of a higher frequency than the first; and a second operating mode having a third communications band that is higher in frequency than the first and second communications bands as claimed therein is not present in the invention of Groups I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of an electronic device having an antenna; and a conductive loop between antenna feed terminals, this technical feature is not a special technical feature as it does not make a contribution over the prior art in view of US 2010/0271271 A1 (WU) 28 October 2010 (28.10.2010) paragraphs 8-13.

Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.