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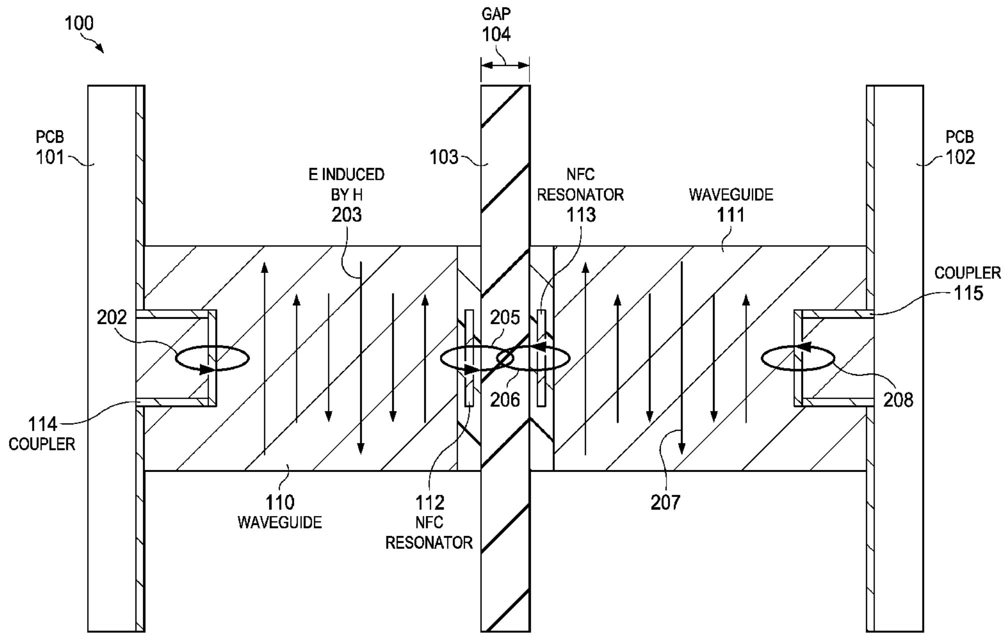


FIG. 2

**(57) Abstract:** In described examples of a system (100), a first waveguide (110) has a first resonator (112) coupled to an end of the first waveguide (110). A second waveguide (111) has a second resonator (113) coupled to the second waveguide (111). The first resonator (112) is spaced apart from the second resonator (113) by a gap (104) distance. Transmission of a signal (203) propagated by the first waveguide (110) across the gap (104) to the second waveguide (111) is enhanced by a confined near field mode magnetic field (205) produced by the first resonator (112) in response to a propagating wave that is coupled to the second resonator (113).

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# CONTACTLESS INTERFACE FOR MM-WAVE NEAR FIELD COMMUNICATION

[0001] This relates generally to near field communication (NFC) in place of physical/ohmic contacts for communication among system modules.

## BACKGROUND

[0002] In electromagnetic and communications engineering, the term waveguide may refer to any linear structure that conveys electromagnetic waves between its endpoints. The original and most common meaning is a hollow metal pipe used to carry radio waves. This type of waveguide is used as a transmission medium for such purposes as connecting microwave transmitters and receivers to their antennas, in equipment such as microwave ovens, radar sets, satellite communications, and microwave radio links.

[0003] A dielectric waveguide employs a solid dielectric core instead of a hollow pipe. A dielectric is an electrical insulator that can be polarized by an applied electric field. When a dielectric is placed in an electric field, electric charges do not flow through the material as they do in a conductor, but only slightly shift from their average equilibrium positions causing dielectric polarization. Because of dielectric polarization, positive charges are displaced toward the field and negative charges shift in the opposite direction. This creates an internal electric field, which reduces the overall field within the dielectric itself. If a dielectric is composed of weakly bonded molecules, those molecules become polarized, and they also reorient, so their symmetry axis aligns to the field. The term "insulator" implies low electrical conduction, but "dielectric" typically describes materials with a high polarizability; which is expressed by a number called the dielectric constant (εk) and/or by a number called the relative permittivity (εr). The term insulator generally indicates electrical obstruction, and the term dielectric indicates the energy storing capacity of the material by polarization.

[0004] The electromagnetic waves in a metal-pipe waveguide may be imagined as travelling down the guide in a zig-zag path, being repeatedly reflected between opposite walls of the guide. For the particular case of a rectangular waveguide, an exact analysis can be based on this view. Propagation in a dielectric waveguide may be viewed in the same way, with the waves confined to the dielectric by total internal reflection at its surface.

**[0005]** Near field communication (NFC) is a wireless technology, allowing two devices to communicate over a short distance of approximately 10 cm or less. Various protocols using NFC have been standardized internationally within NFC Forum specifications, such as defined in ISO/IEC 18092, ECMA-340 and ISO 14443. NFC allows a mobile device to interact with a subscriber's immediate environment. With close-range contactless technology, mobile devices may be used as credit cards, to access public transportation, to access secured locations, and many more applications. Contactless systems are commonly used as access control IDs (e.g. employee badges) and payment systems for public transportation etc. More recently, credit cards are beginning to include NFC capability.

SUMMARY

**[0006]** In described examples of a system, a first waveguide has a first resonator coupled to an end of the first waveguide. A second waveguide has a second resonator coupled to the second waveguide. The first resonator is spaced apart from the second resonator by a gap distance. Transmission of a signal propagated by the first waveguide across the gap to the second waveguide is enhanced by a confined near field mode magnetic field produced by the first resonator in response to a propagating wave that is coupled to the second resonator.

BRIEF DESCRIPTION OF THE DRAWINGS

**[0007]** FIGS. 1-2 are side views of a system illustrating near field coupling across a gap between two waveguides with the aid of resonators.

**[0008]** FIGS. 3A-3C, 4 illustrate an example waveguide coupler and resonator placed in the waveguides of FIGS. 1-2 in more detail.

**[0009]** FIGS. 5-7 are plots illustrating simulated operation of the system of FIGS. 1-2.

**[0010]** FIG. 8 is a block diagram of an example system that uses waveguides with resonators for NFC communication between modules.

**[0011]** FIGS. 9 is a more detailed illustration of modules for the system of FIG. 8.

**[0012]** FIG. 10 is a pictorial illustration of the example system of FIG. 8.

**[0013]** FIG. 11 is a flow chart illustrating operation of near field communication (NFC) between adjacent modules.

**[0014]** FIG. 12 is a cross sectional view of another embodiment of a system using near field coupling across a gap.

[0015] FIGS. 13-15 illustrate other embodiments of systems using resonators to improve coupling efficiency of NFC across a gap between waveguides.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0016] In the drawings, like elements are denoted by like reference numerals for consistency.

[0017] As frequencies in electronic components and systems increase, the wavelength decreases in a corresponding manner. For example, many computer processors now operate in the gigahertz realm. As operating frequencies increase to sub-terahertz, the wavelengths become short enough that signal lines that exceed a short distance may act as an antenna and signal radiation may occur. For example, in a material with a low dielectric constant of 3, such as a printed circuit board, a 100 GHz signal will have a wavelength of approximately 1.7mm. Thus, a signal line that is only 1.7mm in length may act as a full wave antenna and radiate a significant percentage of the signal energy in the material.

[0018] Waves in open space propagate in all directions, as spherical waves. In this way, in the far-field regime, they lose their power proportionally to the square of the distance; that is, at a distance R from the source, the power is the source power divided by $R^2$. Such random wave propagation may also result in interference to other systems that are located nearby and be in violation of emission limits set by standard bodies such as FCC and IEC.

[0019] A waveguide is useful to transport high frequency signals over relatively long distances. The waveguide confines the wave to propagation in one dimension, so that under ideal conditions the wave loses no power while propagating. Electromagnetic wave propagation along the axis of the waveguide is described by the wave equation, which is derived from Maxwell's equations, and where the wavelength depends upon the structure of the waveguide, and the material within it (air, plastic, vacuum, etc.), and on the frequency of the wave. Commonly-used waveguides are only of a few categories. The most common kind of waveguide is one that has a rectangular cross-section, one that is usually not square. Often, the long side of this cross-section is twice as long as its short side. These are useful for carrying electromagnetic waves that are horizontally or vertically polarized.

[0020] For the exceedingly small wavelengths encountered for sub-THz radio frequency (RF) signals, dielectric waveguides perform well and are much less expensive to fabricate than hollow metal waveguides. Furthermore, a metallic waveguide has a frequency cutoff determined by the size of the waveguide. Below the cutoff frequency, no propagation (of the electromagnetic field) occurs. Dielectric waveguides have a wider range of operation without a fixed cutoff point.

**[0021]** Using NFC coupling with waveguides to distribute signals between various modules may provide a low cost interconnect solution. Embodiments may provide a way to interface removable system modules without using physical/ohmic contacts.

**[0022]** FIGS. 1-2 are side views of a portion of an example system 100 illustrating near field communication (NFC) across a gap 104 between two waveguides 110, 111 with the aid of resonators 112, 113. In this example, substrate 101 may contain or be coupled to high frequency circuitry that is configured to generate a radio frequency (RF) signal. In some embodiments, the RF signal may have a fundamental frequency in an example range of approximately 10-200 GHz. The substrate 101 may be a printed circuit board (PCB) implemented using any commonly used or later developed material used for electronic systems and packages, such as: fiberglass, plastic, silicon, ceramic, Plexiglas, etc.

**[0023]** A waveguide 110 may be located adjacent substrate 101 and extend for a distance D1 away from substrate 101. As described hereinabove, waveguide 110 may be a metallic waveguide, a dielectric waveguide, a dielectric filled metallic waveguide, or other known or later developed transmission media for propagation of RF signals. A coupler 114 may be fabricated on substrate 101 for launching the RF signal into waveguide 110. For example, coupler 114 may be a shorted loop of a microstrip connected to the circuitry that generates the RF signal. In another embodiment, coupler 114 may be a differential loop in which a microstrip on each side is fed differentially. Other embodiments may use other known or later developed structures for launching an RF signal into waveguide 110.

**[0024]** Similarly, another substrate 102 may contain or be coupled to high frequency circuitry that is configured to receive an RF signal. In some embodiments, the RF signal may have a fundamental frequency in an example range of approximately 10-200 GHz. The substrate 102 may be a PCB implemented using any commonly used or later developed material used for electronic systems and packages, such as: fiberglass, plastic, silicon, ceramic, Plexiglas, etc.

**[0025]** A waveguide 111 may be located adjacent substrate 102 and extend for a distance D2 away from substrate 102. As described hereinabove, waveguide 111 may be a metallic waveguide, a dielectric waveguide, a dielectric filled metallic waveguide, or other known or later developed transmission media for propagation of RF signals. A coupler 115 may be fabricated on substrate 102 for receiving the RF signal from waveguide 110. For example, coupler 115 may be a shorted loop of a microstrip connected to the circuitry that receives the RF signal. In another embodiment, coupler 114 may be a differential loop in which a microstrip on each side is fed differentially. Other embodiments may use other known or later developed structures for receiving an RF signal from waveguide 111.

**[0026]** A resonator 112 may be fabricated on the end of waveguide 110 opposite from coupler 114, as described hereinbelow. Similarly, a resonator 113 may be fabricated on an end of waveguide 111 opposite coupler 115. In this example, the end of waveguide 110 containing resonator 112 is spaced apart from the end of waveguide 111 containing resonator 113 by a gap distance 104. For example, the gap may simply be a space between the two ends and be filled with air. In some embodiments, a solid material 103 may fill all or a portion of gap 104. Solid material 103 may be a dielectric or insulating material, such as plastic, glass, fiberglass, ceramic, Plexiglas, etc.

**[0027]** Distance D1, D2 may be relatively short for applications in which the substrates are packaged within system modules that are located close together, examples of which will be described hereinbelow. In other applications, D1 and/or D2 may be long when substrate 101 is located a longer distance from substrate 102. For example, substrate 101 may be separated from substrate 102 by several inches, several feet, or even hundreds of feet or more. Waveguides 110, 111 allow signal confinement and propagation with low loss over long distances.

**[0028]** FIG. 2 illustrates the operation of NFC in system 100. For example, launch structure 114 may be a shorted loop of microstrip or a differential loop that creates a magnetic field 202 in waveguide 110 to match the TE01 mode H-field of waveguide 110. This allows for transitioning from a microstrip propagation mode to a waveguide propagation mode. H-field 202 then induces a propagating E-field 203 according to waveguide propagation principles. When propagating E-field 203 interacts with resonator 112, a current is generated that produces confined near field mode magnetic field 205. Confined near field mode magnetic field 205 is essentially a non-radiating evanescent field that magnetically couples with resonator 113 across gap 104 to produce an induced current in resonator 113. The induced current in resonator 113 then creates a magnetic field 206 that induces propagating E-field 207 in waveguide 111. When E-field 207 reaches coupler 115, a magnetic field 208 generates an RF signal that may then be routed to receiver circuitry on substrate 102.

**[0029]** In this manner, an RF signal may be transferred from circuitry on substrate 101 to circuitry on substrate 102 via waveguides 110, 111 across gap 104 with minimal loss or radiation to adjacent systems/components due to a confined near field mode magnetic field produced by resonator at the end of each waveguide adjacent the gap.

**[0030]** FIGS. 3A-3C, 4 illustrate an example coupler and resonator placed in the waveguides of FIGS. 1-2 in more detail. FIG. 3B is an end view looking into waveguide 310 through substrate 301. The description here may be applied to both of waveguides 110, 111 in FIG. 1-2. FIG. 3A illustrates an example IC 320 that may contain RF circuitry that is connected to waveguide coupler 314. IC 320 may include receiver circuitry for processing an RF signal received on coupler 314 via waveguide 310 or transmitter circuitry for producing an RF signal that is transmitted by coupler 314 into waveguide 310. For example, in some embodiments, IC 320 may contain both transmitter circuitry and receiver circuitry.

**[0031]** Also, for example, coupler 314 may be a discrete loop that is soldered to substrate 301. Coupler 314 may be a differential loop which has a microstrip 321 on each side to feed it differentially, as illustrated in FIG. 3B. In FIG. 3A, copper trace 321 is configured as a microstrip over ground plane 322. FIG. 3C illustrates another implementation in which one side of the loop 314 may be shorted 323 to ground for a single-ended feed.

**[0032]** Referring to FIG. 3B, resonator 312 is essentially an open loop that is configured to interact with a propagating wave on the waveguide to which it is mounted. For example, resonator 312 may be fabricated on a single layer substrate and attached to the end of waveguide 310, using known or later developed techniques, such as: an adhesive, by soldering mounting pads on the substrate to the metal waveguide, etc. In some embodiments, waveguide 310 may have a dielectric core. In this case, resonator 312 may be formed on the end of the dielectric core using an additive process, such as inkjet printing using conductive ink. In another embodiment, resonator 312 may be mounted on a dielectric such as dielectric 103 (referring again to FIG. 1) that is adjacent to the end of waveguide 310.

**[0033]** FIG. 4 is an isometric view of coupler 112 and 113 illustrating how the couplers may be oriented with respect to each other and spaced apart by gap 104.

**[0034]** FIG. 5 is a filed strength plot illustrating simulated operation of the system of FIGS. 1-2. In this example, E-field 203 is propagating through waveguide 110 in a direction indicated by vector 502. When E-field 203 encounters resonator 112, a strong confined near field mode magnetic field is produced that magnetically couples across gap 104 to resonator 113 without significant loss or radiation to nearby systems/components. The confined field acts as an evanescent field that does not radiate.

**[0035]** FIG. 6 is a plot illustrating coupling efficiency versus gap distance, measured in the wavelength of the propagating signal. Plot line 602 illustrates a system without resonators, while plot line 604 illustrates operation of a system with resonators placed at the ends of the waveguides on either side of a gap. An efficiency improvement of approximately 1dB may be observed for an example gap of 0.35 wavelength with the use of resonators. As described hereinabove, for a frequency of 100 GHz, the wavelength is approximately 1.7 mm in a material with a dielectric constant of 3.

**[0036]** FIG. 7 is a plot illustrating coupling efficiency versus frequency. Plot line 702 illustrates a system without resonators, while plot line 704 illustrates operation of a system with resonators placed at the ends of the waveguides on either side of a gap. In this example, the waveguide is configured to have propagation mode 1 starting at 100 GHz, and propagation mode 2 starting at 200 GHz. In this case, coupled resonators inserted into the gap are designed to have a limited bandwidth and may increase the coupling efficiency over a selected band of frequencies.

**[0037]** In another embodiment, several resonators tuned for different ranges of frequencies may be inserted to increase the bandwidth. In another embodiment, wide band resonators may be used to increase the bandwidth.

**[0038]** FIG. 8 is a block diagram of an example system that uses waveguides with resonators for NFC communication between modules. System 800 is an example programmable logic controller that uses guided NFC communication between modules. A programmable logic controller (PLC), or programmable controller, is a digital computer used for automation of typically industrial electromechanical processes, such as control of machinery on factory assembly lines, amusement rides, light fixtures, etc. PLCs are used in many machines, in many industries. PLCs are designed for multiple arrangements of digital and analog inputs and outputs, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact. Programs to control machine operation are typically stored in battery-backed-up or non-volatile memory. A PLC is an example of a "hard" real-time system because output results must be produced in response to input conditions within a limited time, otherwise unintended operation will result. PLC systems are known and not described in detail herein (e.g., see

"Programmable Logic Controller", Wikipedia, as of Dec 1, 2015, which is incorporated by reference herein).

**[0039]** In this example, several modules are referred to as "line cards". Various types of line cards may be installed in a chassis or rack and configured for various purposes, such as: to control manufacturing processes, to control the heating and cooling in a building, to control medical equipment, etc. Accordingly, electrical isolation is often needed or desirable to prevent ground loops or other interactions between various pieces of equipment that are being controlled. In the past, various types of isolation devices have been used, such as: optical isolators, transformers, etc.

**[0040]** This example has a power supply line card 802, a data communication line card 810, and several processing line cards 820, 840, 841. FIG. 8 shows five line card modules, but an example chassis may accommodate ten or more modules. A system using line cards is illustrated herein, but embodiments are not limited to line cards. Various types of modules may use the communication techniques described herein to provide reliable communication between removable modules.

**[0041]** In this example, supply line card 802 is coupled to a source of power and in-turn may produce one or more voltages that may be distributed via a bus 804 that may be coupled to each of the line cards via connectors such as connector 805. Usually, voltage bus(es) 804 may be included in a backplane that provides support for the connectors 805.

**[0042]** For example, data communication line card 810 may be configured to send and receive data via a communication channel to a remote host or another rack or chassis. Various types of communication line card 810 may accommodate a wireless or wired interface. Also, for example, an internet connection to a local or a wide area net may be provided by line card 810. Alternatively, a wireless connection to a Wi-Fi network or to a cellular network may be provided by line card 810.

**[0043]** For example, processing line card 820 may include front end interface logic 830, processing logic 831, and aggregator logic 832. Front end interface logic 830 may be of various types to provide interconnection to equipment that is being controlled, such as: input and output signals, RS232/422/485 compatible signals, digital signals, analog signals, etc. Various types of logic may be provided, such as: analog to digital converters (ADC), digital to analog converters (DAC), relays, contacts, etc. Processing logic 831 may include various types of hardwired and programmable logic, microcontrollers, microprocessors, memory, etc. Line cards 840, 841, etc. may be identical or similar to line card 820 and may include various types and combinations of processing and interface logic as needed for a given control task.

**[0044]** In this example, each line card is configured to allow it to communicate with its nearest neighbor on both sides. For example, line card 810 may transmit via transmitter 811 to line card 820 which has a receiver 824. Similarly, line card 820 may transmit via transmitter 823 to receiver 815 on line card 810. At the same time, line card 820 may transmit via transmitter 822 to adjacent line card 840 and receive via receiver 821 from adjacent line card 840.

**[0045]** In a similar manner, each line card in system 800 may communicate with each other line card in a daisy chain manner. Each line card includes an aggregator/de-aggregator logic function, such as 832 on line card 820, that allows each line card to recognize communication on the daisy chain intended for it. The aggregator/de-aggregator function also allows a line card to originate a communication packet that is then provided to the daisy chain and then propagated through adjacent line cards to a final destination on a target line card. In this embodiment, the daisy chain operates in a similar manner to an internet network protocol and each aggregator 832 functions as an internet interface. In another embodiment, a different type of known or later developed peer to peer protocol may be used.

**[0046]** As described hereinabove, NFC may be used as the transport vehicle to communicate between each adjacent line card. As described hereinbelow, waveguide segments (such as waveguide 815, 825 and 816, 826) may be used to guide the NFC between each adjacent line card module in order to minimize signal spreading and interface to other systems and devices.

**[0047]** FIG. 9 is a more detailed illustration of modules for the system of FIG. 8. FIG. 9 illustrates two example line card modules 921, 922 that are representative of the various modules 810, 820, 840, etc. of system 800. Module 921 may include a substrate 901 on which various circuit components are mounted, such as an integrated circuit (IC) 951 that includes transmitter(s) and receivers(s), such as transmitter 823 and receiver 824 and/or transmitter 822 and receiver 821, of line card 820. In some embodiments, a separate IC may exist for each transmitter and receiver. For example, in another embodiment, one or more receivers and transmitters may be formed in a single IC. Similarly, module 922 may include substrate 902 on which are mounted various circuit components, such as an integrated circuit (IC) 952 that includes transmitter(s) and receivers(s).

[0048] Integrated circuits 951, 952 may also include aggregation logic, processing logic and front end logic, or additional ICs may be mounted on substrate 901, 902 that contain aggregation logic, processing logic, and front end logic. For example, substrate 901 may be a single or a multilayer printed circuit board. IC 951 and other ICs may be mounted on substrate 901 using through hole or surface mount technology using solder bumps or bonding depending on the frequency of operation, or other known or later developed packaging technologies. Substrate 901, 902 may be any commonly used or later developed material used for electronic systems and packages, such as: fiberglass, plastic, silicon, ceramic, Plexiglas, etc.

[0049] Substrates 901, 902 may also contain a waveguide (WG) coupler 914 that is connected to the receiver and/or transmitter that is contained within IC 951. WG coupler 915 may also be coupled to the receiver and/or transmitter that are contained within IC 951, 952. WG coupler 914, 915 may be similar to couplers 314, referring again to FIGS. 3A and 3B. The couplers may be separate structures that are mounted on substrate 901, or they may be embedded within substrate 901.

[0050] A waveguide 910 may be mounted in a position that places it approximately centered over WG coupler 914. Similarly, a waveguide 911 may be mounted in a position that places it approximately centered over WG coupler 915. In this manner, a majority of the electromagnetic energy that is emanated by WG coupler 914 will be captured and confined by waveguide 910 and thereby directed to an adjacent module with minimal external radiation and signal loss.

[0051] As described hereinabove, a resonator may be fitted in the end of waveguides 910, 911 in order to convert a propagating wave in each waveguide to/from a confined near field mode evanescent magnetic field around the resonator to allow NFC across gap distance 904. Embodiments may operate in near field mode in which the separation between adjacent modules is a fraction of the wavelength of the frequency being transmitted by the transmitter(s) in IC 951. For example, transmission frequencies in a range of 100GHz to 200GHz may be used. However, some embodiments may use frequencies that are higher or lower than this range. A 100 GHz signal will have a wavelength of approximately 3 mm in air.

[0052] A shield 963 may be provided between left WG coupler 915 and right WG coupler 914 to minimize "back scatter" of the field produced by each WG coupler. For example, shield 963 may be a conductive layer connected to a ground reference for the module. Shield 963 is spaced apart from each coupler 914, 915 by a distance greater than lambda/10, where lambda is the wavelength of the signal being emitted by the couplers, in order to avoid capacitance effects that may reduce the bandwidth of the coupler. For example, the wavelength of a 30GHz signal in a dielectric having an $\varepsilon_R$ of 1 is approximately 10.0 mm. In this example, substrate 901 is a typical PWB material that has an $\varepsilon_R$ of approximately 1.0. Therefore, as long as the shield is spaced away from each coupler by a distance 973 of at least 1mm, then capacitance effects should be minimized in a system operating at 30 GHz. Lower frequency operation may require larger spacing.

**[0053]** Near field mode may produce an evanescent field to couple two adjacent resonators 912, 913. Evanescent fields by nature exhibit an exponential decay with distance away from the source. By virtue of near proximity between resonator 912 of module 921 and another resonator 913 in an adjacent module 922 that is only a few mm's away, a reasonable TX-to-RX signal coupling may be achieved using the evanescent field in near field mode while mitigating emission limits/concerns outlined per FCC Part 15.

**[0054]** The best analogy would be that of a transformer. A strong self-coupling between coils results in reduced leakage to the external world. Furthermore, any leakage may be considered unintentional. The requirements for unintentional radiation per FCC is greatly relaxed compared to those for intentional emissions.

**[0055]** Module 921 may be enclosed in a housing that is roughly indicated at 961, 961. One side of the housing is illustrated as panel 961, and the other side of the housing is illustrated as panel 962 (e.g., metal or plastic). Usually, the housing will be a few mm thick.

**[0056]** Also, for example, waveguide 910 may be a dielectric block. Electromagnetic wave propagation through the dielectric block may be described by the wave equation, which is derived from Maxwell's equations, and where the wavelength depends upon the structure of the dielectric block, and the material within it (air, plastic, vacuum, etc.), and on the frequency of the wave. Waveguide 910, 911 may be able to confine the field emitted by WG coupler by having a permittivity and/or permeability that is significantly greater than surrounding materials and/or air which will significantly reduce the wavelength of the electromagnetic field emitted by WG coupler 914. Similarly, waveguide 910, 911 may be able to confine the field emitted by WG coupler by having a permittivity and/or permeability that is significantly lower than surrounding materials and/or air which will significantly increase the wavelength of the electromagnetic field emitted by WG coupler 914. Alternatively, waveguide 910, 911 may be constructed from a metamaterial that causes a significant reduction or increase in wavelength of the electromagnetic field emitted by WG coupler 914.

**[0057]** For example, waveguide 910, 911 may be a dielectric block that has a relative permittivity greater than approximately 2.0. Similarly, waveguide 910, 911 may be a dielectric block that has a relative permeability less than approximately 2.0.

**[0058]** In another embodiment, dielectric waveguide 910 may have a conductive layer around the periphery to further confine and direct an electromagnetic field radiated by WG coupler 914. The conductive layer may use a metallic or non-metallic conductive material to form sidewalls around waveguide 910, 911, such as: metals such as copper, silver, gold, etc., a conductive polymer formed by ionic doping, carbon and graphite based compounds, conductive oxides, etc.

**[0059]** Depending on the material and thickness of module wall 961, waveguide 910 may be simply mounted to be adjacent to an inside surface of module wall 961 such that the radiated signal passes through module wall 961. In some embodiments, a window may be provided in module wall 961, so that an outer surface of waveguide 910 may be positioned flush, slightly indented, or slightly forward of an outside surface of module wall 961. The general location on the surface of the housing where the waveguide is located will be referred to herein as a "port".

**[0060]** FIG. 9 also illustrates a portion of a second module 922 that may be located adjacent module 921. Module 922 may have a housing that includes a panel 962, that will be referred to as a "left" panel. Module 921 may have a panel 961 that will be referred to as a "right" panel. Module 922 may include a substrate 902 that holds various ICs, such as IC 952 that may include a receiver and transmitter, and a WG coupler 914, 915. Module 922 may also include a waveguide 911 that is positioned adjacent left panel 962 and in alignment with WG 910 in module 921.

**[0061]** When module 921 and module 922 are installed in a chassis, right panel 961 will be in close proximity to left panel 962, as indicated at 904. Waveguide 910 of module 921 and waveguide 911 of module 922 are configured so that they are in approximate alignment with each other. In this manner, a signal that is generated by a transmitter in IC 951 may be provided to coupler 914, radiated into waveguide 910 and thereby directed to resonator 912 and then received by resonator 913 of module 922, launched into waveguide 911, received by coupler 914 on substrate 902 and thereby provided to a receiver in IC 952.

**[0062]** Module 921 or 922 may be easily removed from or inserted into a chassis without any wear and tear on contacts that were previously required to communicate signals between modules. Furthermore, NFC using resonators 912, 913 provide complete electrical isolation between module 921 and module 922. An additional isolation mechanism is not required.

**[0063]** FIG. 10 is a pictorial illustration of an example system 1000 that is another view of system 800 of FIG. 8. Backplane 1006 provides a set of connectors 1005 for providing power to each line card, as described with regard to connector 105 of FIG. 1. As shown, each line card module is removable from backplane 1006 by simply pulling the module to disconnect it from connector 1005. Usually, a rack or chassis will also be provided along with backplane 1006 to support the line cards when they are inserted into connectors 1005.

**[0064]** Each line card module is enclosed in a housing, which may be made from plastic or other suitable materials. As described hereinabove, each line card may have a WG coupler, waveguide and resonator arranged to form a contactless communication port on each side of the module. For example, module 1010 may have a port 1055 on the right side of the module while module 1020 may have a port 1056 on the left side of the module that aligns with port 1055 when both modules are plugged into backplane 1006.

**[0065]** Similarly, module 1020 may have another port (not shown) on the right side of the module while module 1040 may have a port (not shown) on the left side of the module that aligns when both modules are plugged into backplane 1006. All of the modules may have similar pairs of ports on both sides of each module to allow daisy chained communication among all of the modules, as described hereinabove.

**[0066]** FIG. 11 is a flow chart illustrating operation of near field communication between modules, as described hereinabove. Also, as described hereinabove, the modules may be part of a programmable logic control system used for industrial, commercial, and residential applications. A usual system may include a rack or chassis into which a set of modules are installed. Each module may communicate with an adjacent neighbor module using near field communication, in which an RF signal generated in one module may be EM coupled to a receiver in an adjacent module using radiative coupling, near field coupling, or evanescent coupling, or any combination of these modes.

**[0067]** For example, a radio frequency (RF) signal may be generated 1102 in a first module. In the example of FIGS. 1-10, the RF signal may have a frequency in the range of 100-200GHz. However, other systems may use RF signals at a higher or lower frequency by adjusting the physical size of the field coupling and field confining components described herein.

**[0068]** An RF electromagnetic field may be emanated 1104 in response to the RF signal from a first waveguide coupler in the first module. For example, the RF electromagnetic field may be the result of a traveling wave formed in a microstrip loop, as described in connection with FIGS. 3A and 3B.

**[0069]** The emanated RF electromagnetic field is confined and directed 1106 by a waveguide in the first module to a resonator at the end of the waveguide. A confined near field mode magnetic evanescent field may be generated by the resonator in response to the propagating electromagnetic field in the waveguide.

**[0070]** The evanescent field may inductively couple 1108 to a similar resonator located at the end of a waveguide in an adjacent second module. As described hereinabove, the two resonators are located in close proximity when the modules are installed in a system and thereby minimize loss of emanated energy to the surroundings. As described hereinabove, this coupling is performed by EM coupling and may use the near field of the emanated electromagnetic field from the resonator. The coupling may also make use of an evanescent field that is formed by the first WG coupler. Some portion of the propagating field (from the waveguide in the first module) may radiate across the gap between modules. Depending on the spacing between the adjacent modules, one or the other or a combination of these coupling modes may occur. For example, this may simplify the process of complying with FCC emission requirements.

**[0071]** The emanated RF electromagnetic field is then propagated 1110 to a second WG coupler in the second module.

**[0072]** A resultant RF signal may then be provided 1112 to an RF receiver on the second module. As described hereinabove, the multiple modules in the system may communicate in a daisy chained manner such that any module may be able to communicate with any other module in the system.

**[0073]** A known standard communication protocol (such as the Internet Protocol) may be used, treating the daisy chained NFC physical media as an Ethernet. The Internet Protocol (IP) is the principal communications protocol in the Internet protocol suite for relaying datagrams across network boundaries. IP has the task of delivering packets from the source host to the destination host solely based on the IP addresses in the packet headers. For this purpose, IP defines packet structures that encapsulate the data to be delivered. It also defines addressing methods that are used to label the datagram with source and destination information. The first major version of IP, Internet Protocol Version 4 (IPv4), is the dominant protocol of the Internet. Its successor is Internet Protocol Version 6 (IPv6).

**[0074]** Another embodiment may use another known or later developed communication protocol for communication using the daisy chained NFC physical media as described herein.

**[0075]** In this manner, embodiments may provide high throughput communication between removable modules of a system using near field communication techniques. The techniques described herein may be less expensive than alternatives, such as optical couplers. NFC allows contactless communication between modules and thereby eliminates the need for additional isolation in systems that may require isolation between modules.

**[0076]** FIG. 12 is a cross sectional view of another embodiment of a portion of a system 1200 using near field coupling across a gap 1204. In this example, a substrate 1201 has a waveguide 1210 formed within the substrate. Substrate 1201 may be a printed circuit board (PCB) implemented using any commonly used or later developed material used for electronic systems and packages, such as: fiberglass, plastic, silicon, ceramic, Plexiglas, etc. An integrated circuit 1220 may be mounted on substrate 1201 and be coupled to waveguide 1210, such as using a coupler similar to coupler 314 of FIG. 3A. Other examples of waveguides formed in a substrate and coupled to an IC are described in Patent No. US 9,306,263, "Interface Between an Integrated Circuit and a Dielectric Waveguide Using a Dipole Antenna and a Reflector," by Juan Herbsommer et al., which is incorporated by reference herein.

**[0077]** A second waveguide 1211 may be configured to interface to waveguide 1210. As described hereinabove, a resonator 1212 placed in the end of waveguide 1211 and an adjacent resonator placed in an end of waveguide 1210 may improve coupling efficiency across gap 1204. In this example, an insulating or dielectric layer 1202 may be formed over a portion or over the entirety of substrate 1201. Layer 1202 may be formed from various materials, such as: silicon dioxide, glass, quartz, ceramic, plastic, etc.

**[0078]** FIG. 13 illustrates a portion of a system 1300 with multiple resonators used for larger gaps. In this example, waveguides 1310, 1311 are separated by a larger gap 1304. As described hereinabove, resonators 1312, 1313 may be placed in the ends of waveguides 1310, 1311 to improve coupling efficiency across gap 1304. However, referring again to FIG. 6, coupling efficiency decreases as the gap gets wider. Beyond approximately a half wavelength gap the efficiency may be too low for good results.

**[0079]** For example, installing one or more resonators 1314 spaced across a gap may allow the effective length of the gap between each pair of resonators to be maintained below approximately 0.5 wavelength.

**[0080]** FIG. 14 illustrates a portion of a system 1400 in which resonators are mounted on a dielectric adjacent the end of a waveguide 1410, 1411. As described hereinabove, resonators 1412, 1413 may improve coupling efficiency across gap 1404. In this example, resonators 1412, 1413 may be applied to a surface of a dielectric 1461, 1462 that is forming all or a portion of the gap. For example, referring again to FIG. 9, dielectric 1461 may represent the right panel 961 of a module while dielectric 1462 may represent a left panel 962 of a module. In this manner, waveguides 1410, 1411 may be simple waveguides that are positioned adjacent resonators 1412, 1413 when each module is assembled.

**[0081]** FIG. 15 illustrates a portion of a system 1500 in which waveguide 1510 and waveguide 1511 form a "T" intersection with a gap 1504 between them. In this example, resonators 1512, 1513 may be installed in the waveguides to improve efficiency of coupling across gap 1504. In other embodiments, other intersection configurations may also be improved with resonators, such as: a 90 degree bend intersection, a 45 degree bend intersection, etc.

**[0082]** Various other embodiments are possible. For example, a programmable logic controller system is described herein, but other types of modular systems may embody aspects of example embodiments to improve reliability.

**[0083]** Modules in which the guided NFC ports are located on the side of the module are described herein, but a port may be located on an edge of a module with a mating port located on a backplane or other surface that is adjacent to the edge of the module, in another embodiment.

**[0084]** A daisy-chained communication configuration is described herein, but other topologies may be formed in another embodiment. For example, a tree topology may be formed by providing a port on the backplane that mates with an edge mounted port in each module.

**[0085]** A simple dielectric block is described herein, but another embodiment may use a metallic or non-metallic conductive material to form sidewalls on the waveguide field confiner, such as: a conductive polymer formed by ionic doping, carbon and graphite based compounds, conductive oxides, etc.

**[0086]** For example, a dielectric or metamaterial waveguide field confiner may be fabricated onto a surface of a substrate or module panel using an inkjet printing process or other 3D printing process.

**[0087]** Dielectric waveguide field confiners with polymer dielectric cores are described herein, but other embodiments may use other materials for the dielectric core, such as ceramics, glass, etc.

**[0088]** Waveguides with a rectangular cross section are described herein, but other embodiments may be easily implemented. For example, the waveguide may have a cross section that is square, trapezoidal, cylindrical, oval, or many other selected geometries.

**[0089]** For example, the dielectric core of a conductive waveguide may be selected from a range of approximately 2.4-12. These values are for commonly available polymer dielectric materials. Dielectric materials having higher or lower values may be used when they become available.

**[0090]** Sub-terahertz signals in the range of 100-200 GHz are described herein, but WG couplers, waveguides with resonators, and systems for distributing higher or lower frequency signals may be implemented using the principles described herein by adjusting the physical size of the waveguide and resonator accordingly.

**[0091]** Components in digital systems may be referred to by different names and/or may be combined in ways not shown herein without departing from the described functionality. In this description, the term “couple” and derivatives thereof mean an indirect, direct, optical and/or wireless electrical connection. Thus, if a first device couples to a second device, that connection may be through a direct electrical connection, through an indirect electrical connection via other devices and connections, through an optical electrical connection, and/or through a wireless electrical connection.

**[0092]** Although method steps may be presented and described herein in a sequential fashion, one or more of the steps shown and described may be omitted, repeated, performed concurrently, and/or performed in a different order than the order shown in the drawings and/or described herein. Accordingly, example embodiments are not limited to the specific ordering of steps shown in the drawings and/or described herein.

**[0093]** Modifications are possible in the described embodiments, and other embodiments are possible, within the scope of the claims.

CLAIMS

What is claimed is:

1. A system comprising:

a first waveguide having a first resonator coupled to an end of the first waveguide; and

a second waveguide having a second resonator coupled to the second waveguide;

wherein the first resonator is spaced apart from the second resonator by a gap distance.

2. The system of claim 1, wherein the second resonator is coupled to an end of the second waveguide.

3. The system of claim 1, wherein the second waveguide is aligned with the first waveguide in a “T” intersection configuration with the gap distance between them, and wherein the second resonator is positioned on a side of the second waveguide at the T intersection.

4. The system of claim 1, wherein the first waveguide and the second waveguide are metallic waveguides.

5. The system of claim 1, further including a one or more additional resonators positioned in a gap between the first resonator and the second resonator.

6. The system of claim 1, wherein the first resonator is a conductive open loop.

7. The system of claim 1, wherein the first waveguide is contained within a first module, and wherein the first module includes:

a substrate on which is mounted a radio frequency (RF) circuit coupled to a first waveguide coupler located on the substrate; and

a housing that surrounds and encloses the substrate, the housing having a first port region on a surface of the housing, wherein the port region forms a portion of the gap distance;

wherein the first waveguide is located between the first waveguide coupler and the first port region on the housing and is configured to propagate near-field and/or evanescently coupled electromagnetic energy emanated from the first waveguide coupler through the first port region.

8. The system of claim 7, wherein the waveguide coupler is a shorted loop with a single end feed from the RF circuitry.

9. The system of claim 7, wherein the waveguide coupler is a differentially fed loop.

10. The system of claim 1, further including:

a substrate; and

a dielectric layer formed on the substrate;

wherein the first waveguide is positioned on the dielectric layer and wherein the second waveguide is formed in the substrate; and

wherein the first resonator is positioned adjacent the second resonator and spaced apart by the gap distance of the dielectric layer.

11. The system of claim 10, wherein the dielectric layer is glass.

12. A system comprising:

a first module, wherein the first module includes: a substrate on which is mounted a radio frequency (RF) transmitter circuit coupled to a first waveguide coupler located on the substrate; a housing that surrounds and encloses the substrate, the housing having a first port region on a surface of the housing; a first waveguide located between the first waveguide coupler and the first port region on the housing; and a resonator adjacent to an end of the first waveguide at the first port region.

13. The module of claim 12, wherein the first module further includes:

an RF receiver mounted on the substrate and coupled to a second waveguide coupler located on the substrate;

a second waveguide located between the second waveguide coupler and a second port region on the housing; and

a second resonator adjacent to an end of the second waveguide at the second port region.

14. The system of claim 13, wherein the first port region is located on a side of the housing and the second port region is located on an opposite side of the housing, such that when the first module is installed in the system and a second module having a third port region is installed in the system adjacent the first module, the first port region of the first module will align with the third port region of the second module.

15. The system of claim 12, further including:

a backplane with a plurality of locations for attaching a plurality of modules; and

a plurality of modules attached to the backplane, wherein each of the modules has a first port and a second port;

wherein the first port region of each module aligns with the second port region of an adjacent module.

16. The system of claim 12, wherein the first resonator is attached to the inside of wall of the housing in the first port region.

17. A method for transmitting a signal through multiple waveguides, the method comprising:

propagating the signal through a first waveguide in a guided wave transmission mode;

converting the guided wave signal into a confined near field mode magnetic field by a first resonator at an end of the first waveguide;

magnetically coupling the magnetic field to a second resonator at an end of a second waveguide, wherein the second resonator is separated from the first resonator by a gap distance; and

converting the magnetic field back into a guided wave by the second resonator such that the signal propagates through the second waveguide in a guided wave transmission mode.

18. The method of claim 17, wherein converting the guided wave into a confined near field mode magnetic field includes producing a circulating current in the first transducer responsive to the guided wave.

19. The method of claim 17, wherein the waveguides are selected from a group consisting of metallic waveguides, dielectric waveguides, strip lines and transmissions lines.

20. The method of claim 17, wherein the gap distance is filed with a material selected from a group consisting of dielectric, air and glass.

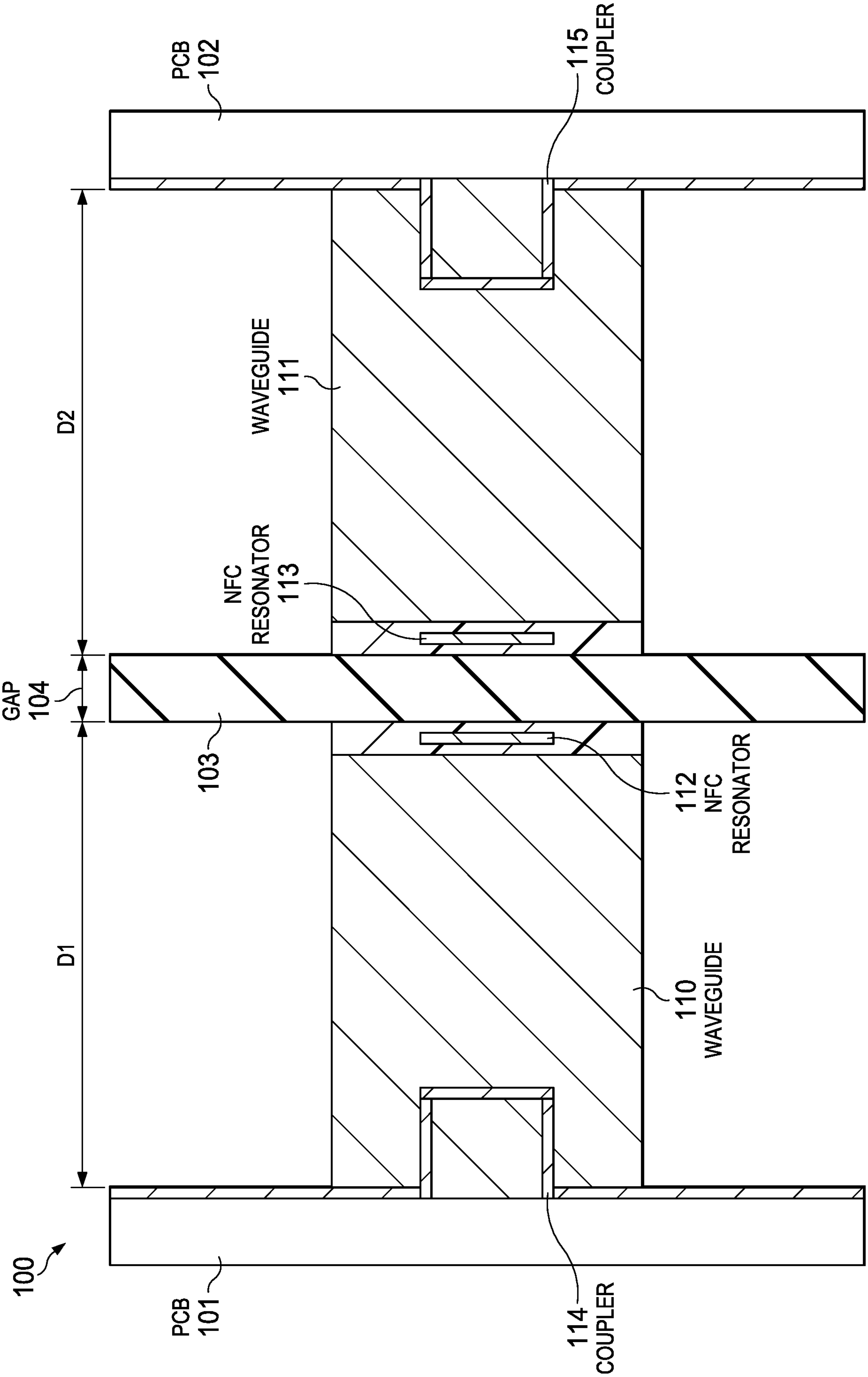

PCB
102
115
COUPLER
WAVEGUIDE
111
D2
NFC
RESONATOR
113
GAP
104
103
112
NFC
RESONATOR
D1
110
WAVEGUIDE
100
PCB
101
114
COUPLER

FIG. 1

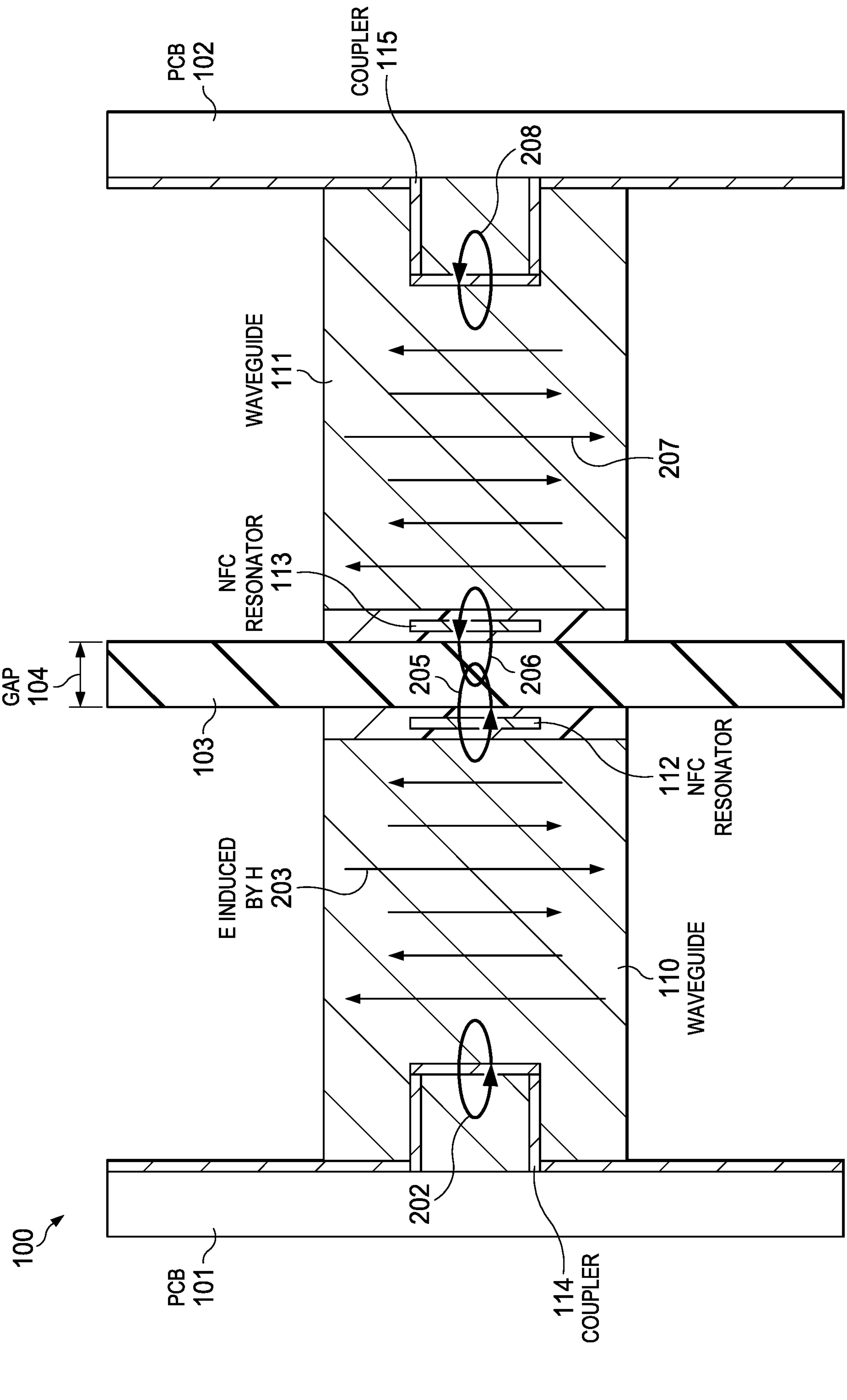

PCB 102
COUPLER 115
208
WAVEGUIDE 111
207
NFC RESONATOR 113
GAP 104
205
206
103
112 NFC RESONATOR
E INDUCED BY H 203
110 WAVEGUIDE
202
100
PCB 101
114 COUPLER

FIG. 2

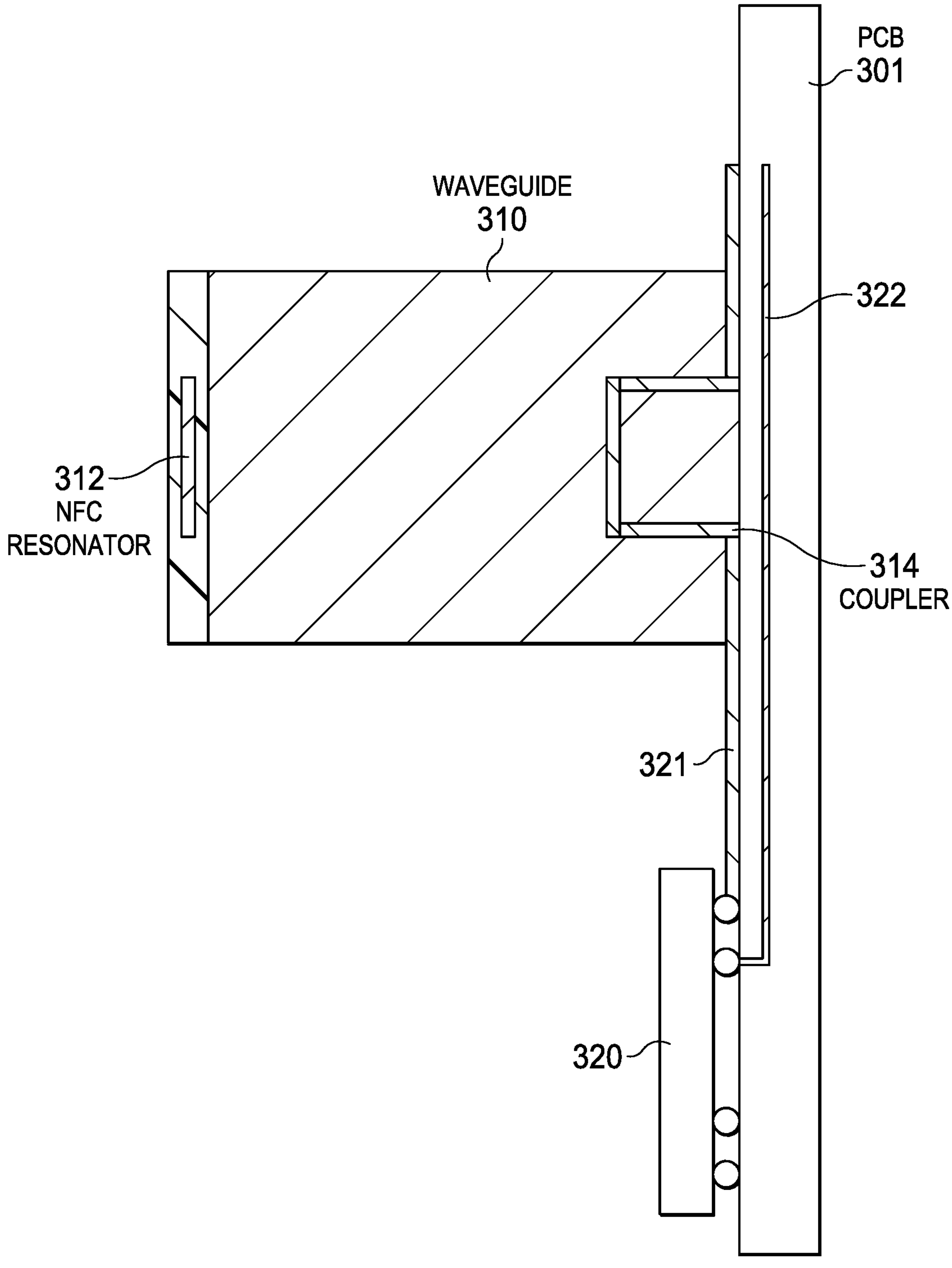

PCB
301
WAVEGUIDE
310
322
312
NFC
RESONATOR
314
COUPLER
321
320

FIG. 3A

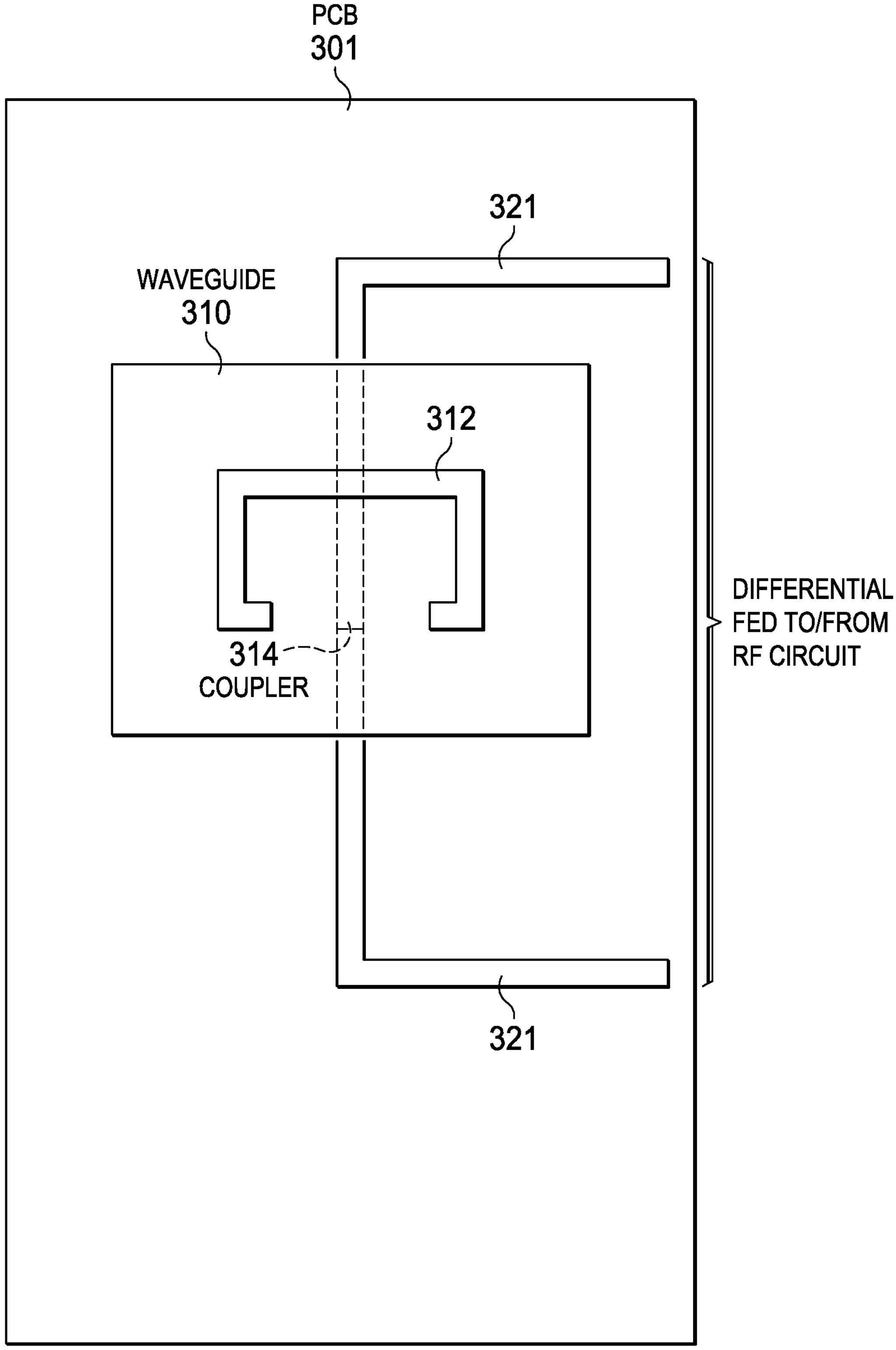

PCB
301
321
WAVEGUIDE
310
312
314
COUPLER
DIFFERENTIAL
FED TO/FROM
RF CIRCUIT
321

FIG. 3B

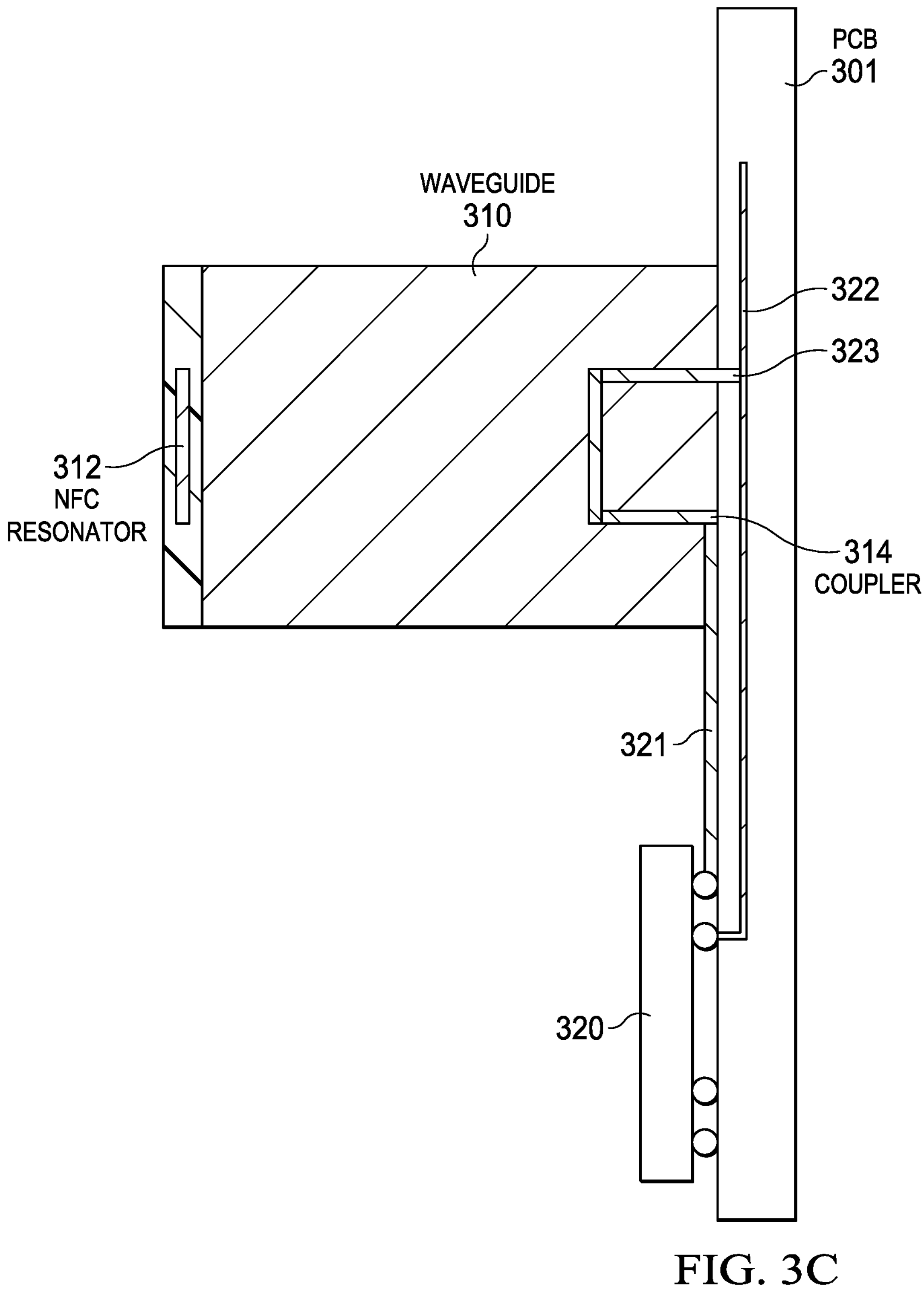

PCB
301
WAVEGUIDE
310
322
323
312
NFC
RESONATOR
314
COUPLER
321
320

FIG. 3C

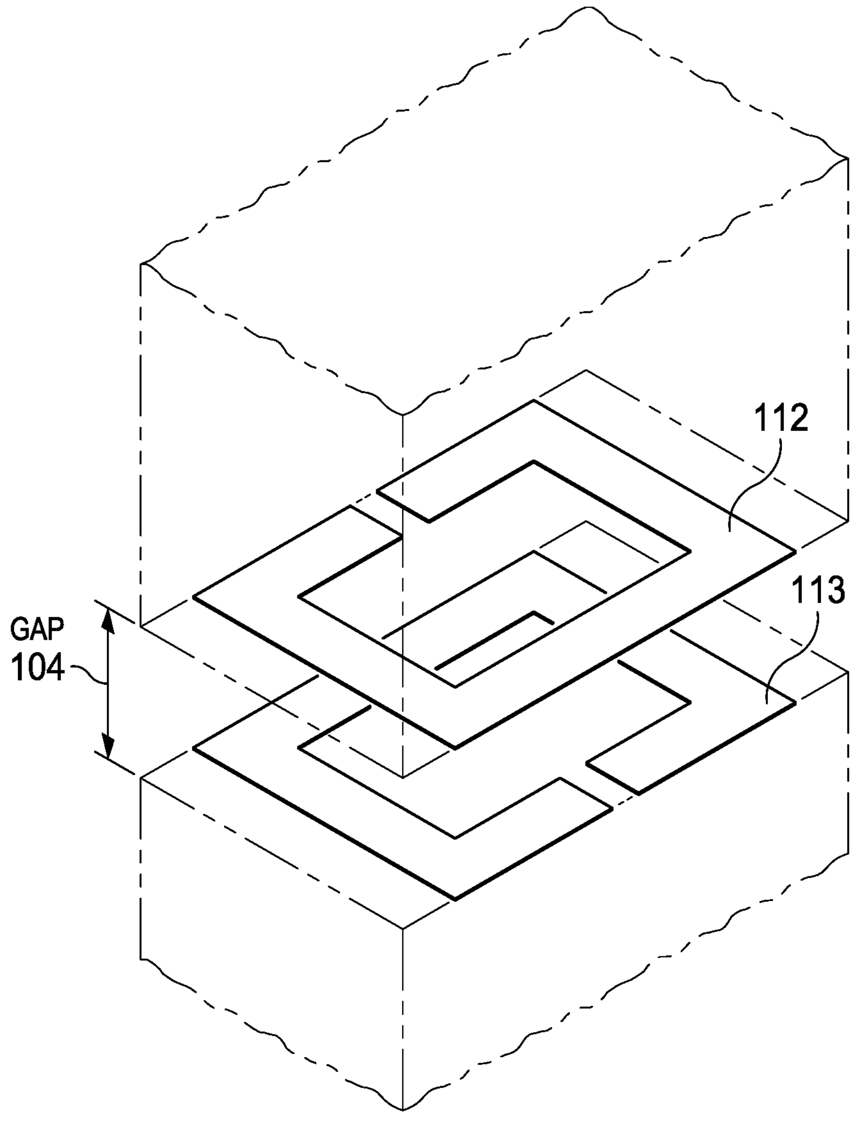



FIG. 4

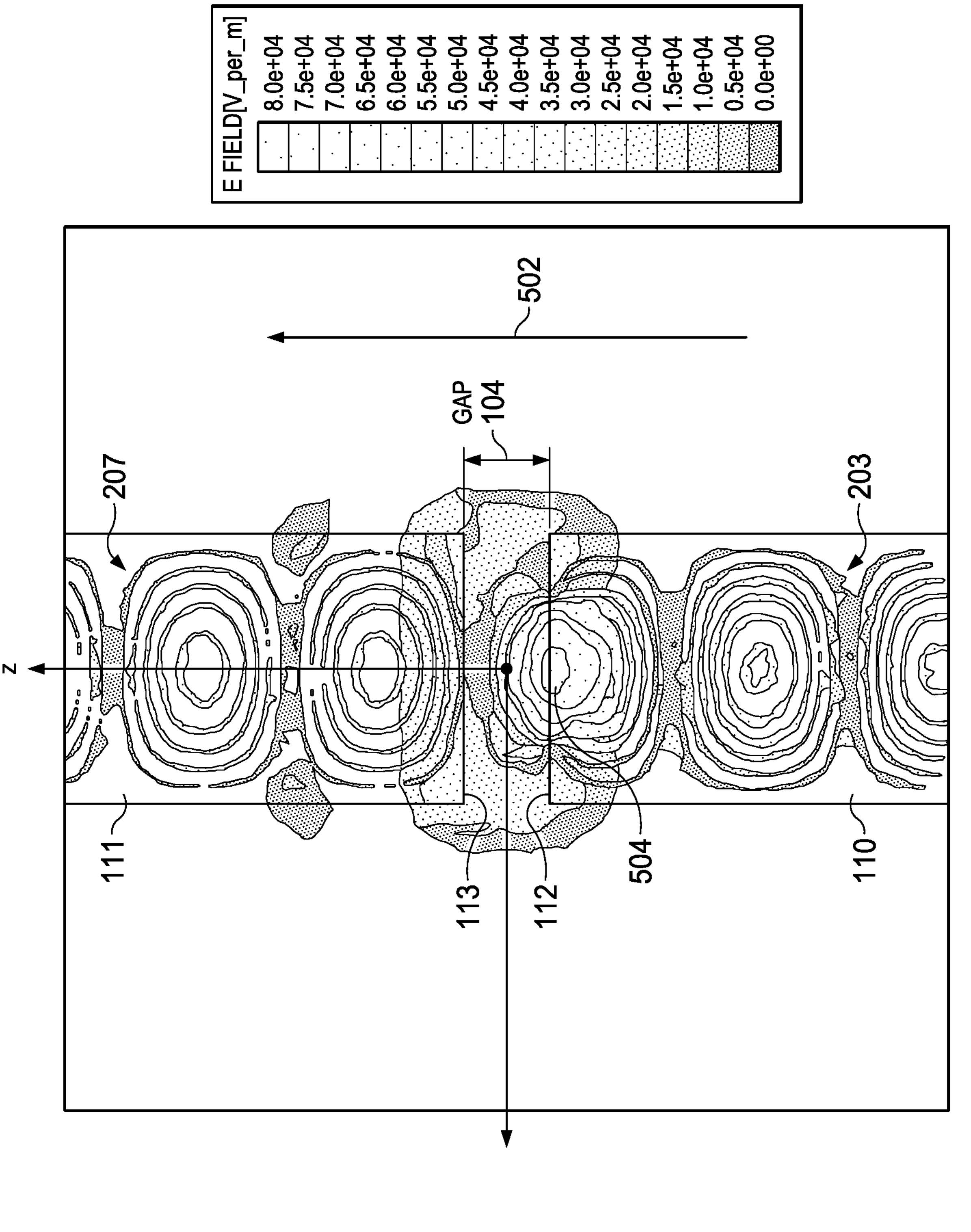

E FIELD[V_per_m]
8.0e+04
7.5e+04
7.0e+04
6.5e+04
6.0e+04
5.5e+04
5.0e+04
4.5e+04
4.0e+04
3.5e+04
3.0e+04
2.5e+04
2.0e+04
1.5e+04
1.0e+04
0.5e+04
0.0e+00
502
GAP
104
207
203
z
111
113
112
504
110
0
2
4 (mm)

FIG. 5

FIG. 6

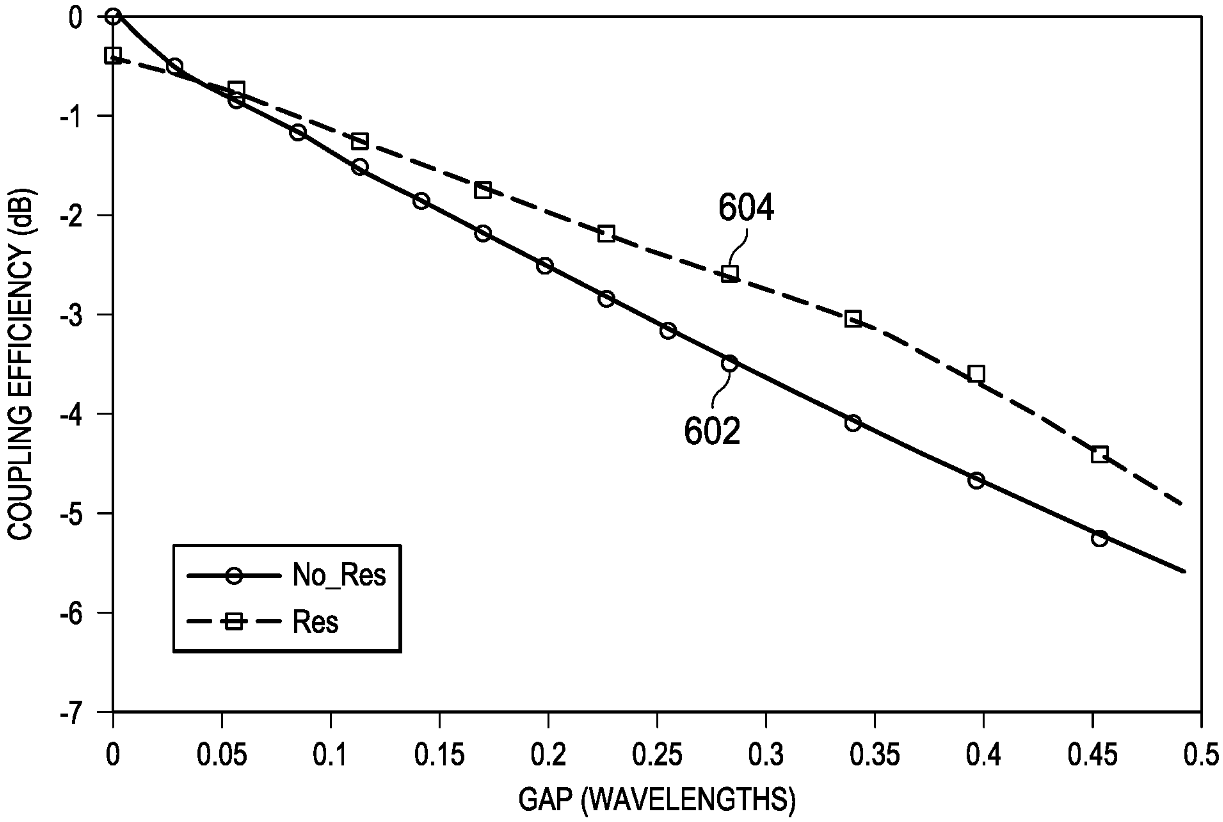
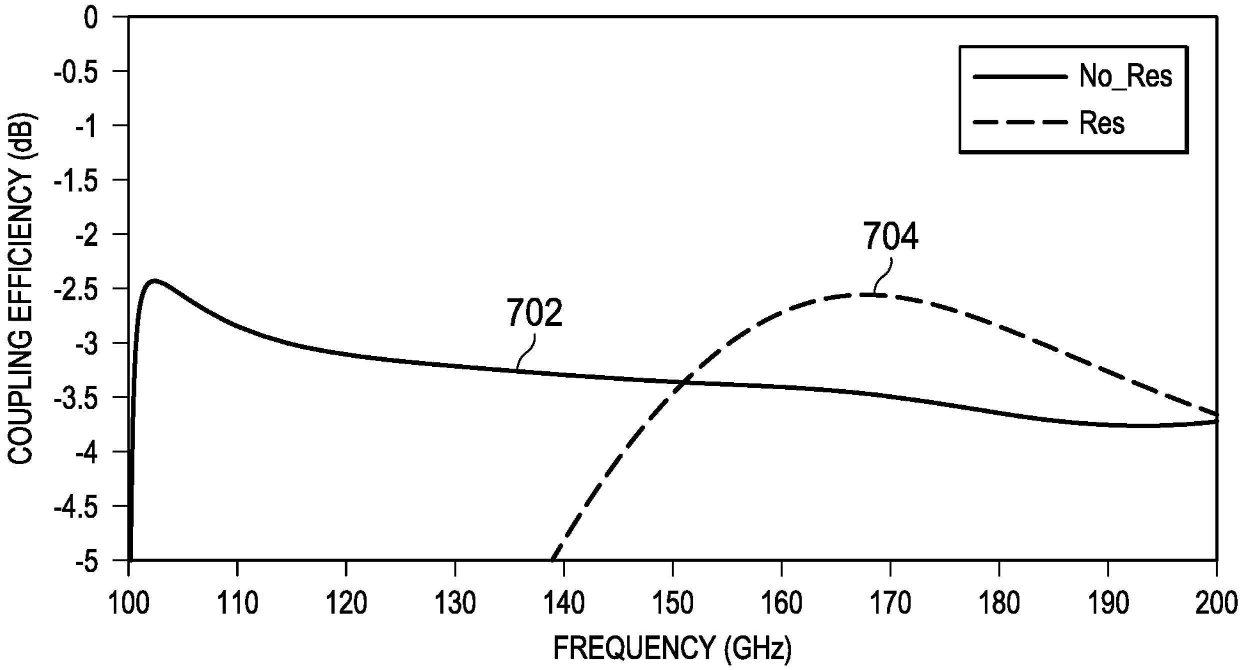

0
-1
-2
-3
-4
-5
-6
-7
COUPLING EFFICIENCY (dB)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
GAP (WAVELENGTHS)
604
602
No_Res
Res

FIG. 7


0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
COUPLING EFFICIENCY (dB)
100
110
120
130
140
150
160
170
180
190
200
FREQUENCY (GHz)
No_Res
Res
704
702

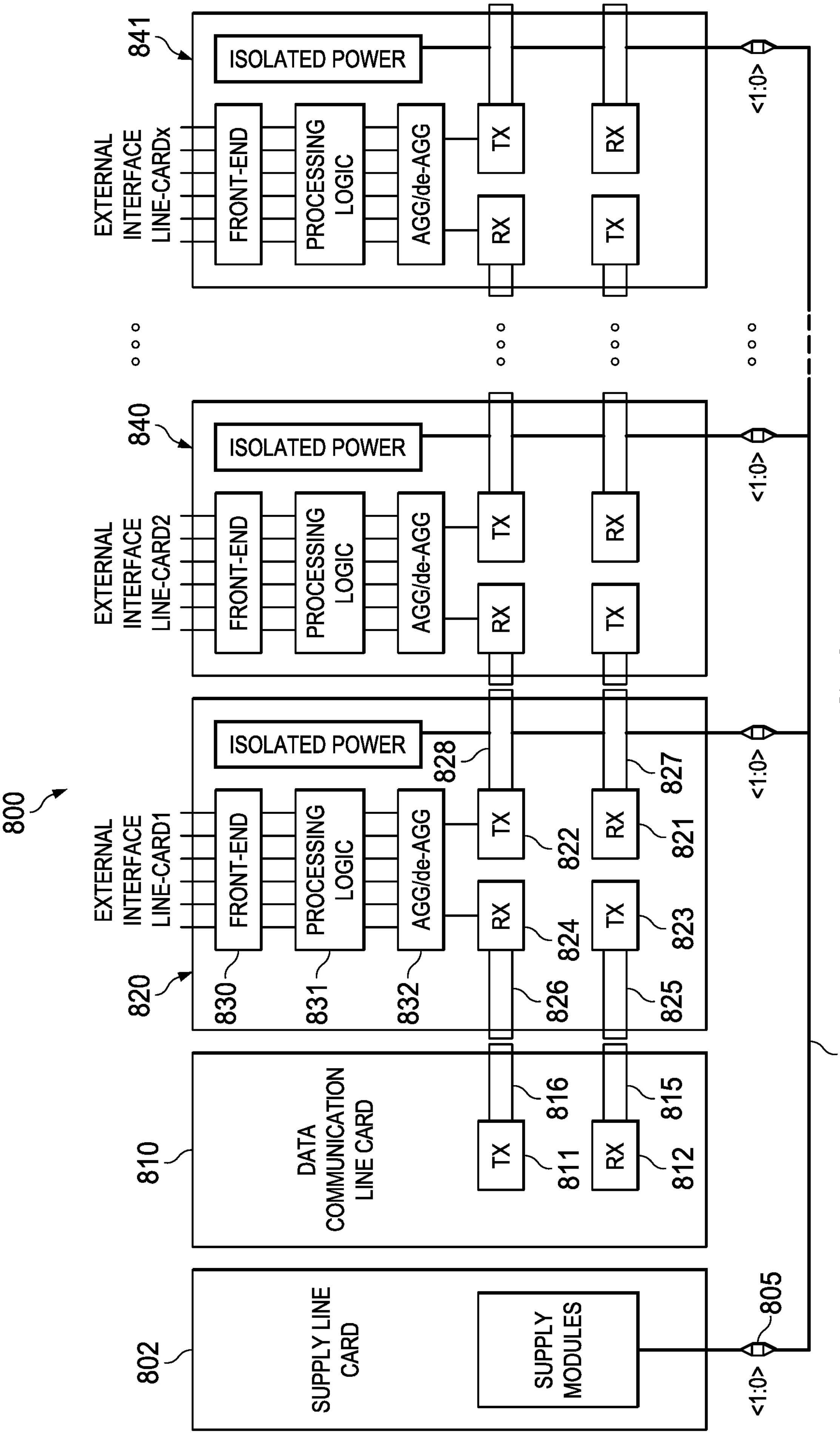

800
802
SUPPLY LINE CARD
SUPPLY MODULES
<1:0>
805
810
DATA COMMUNICATION LINE CARD
TX
RX
811
812
816
815
820
EXTERNAL INTERFACE LINE-CARD1
FRONT-END
PROCESSING LOGIC
AGG/de-AGG
ISOLATED POWER
830
831
832
TX
RX
822
821
824
823
826
825
828
827
840
EXTERNAL INTERFACE LINE-CARD2
841
EXTERNAL INTERFACE LINE-CARDx
804

FIG. 8

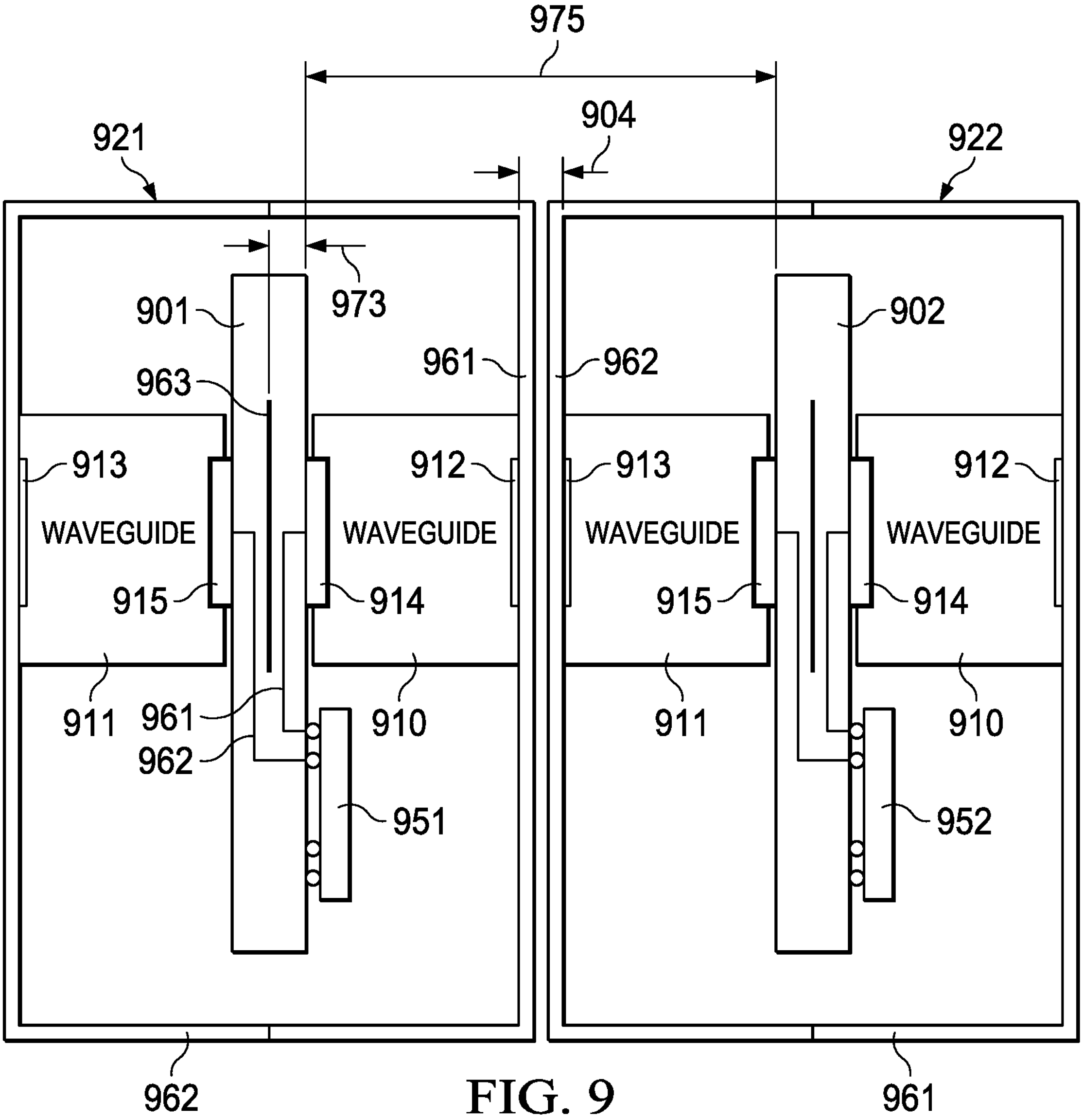

975
904
921
922
973
901
902
963
961
962
913
912
WAVEGUIDE
WAVEGUIDE
WAVEGUIDE
WAVEGUIDE
915
914
911
910
961
962
951
952
962
961

FIG. 9

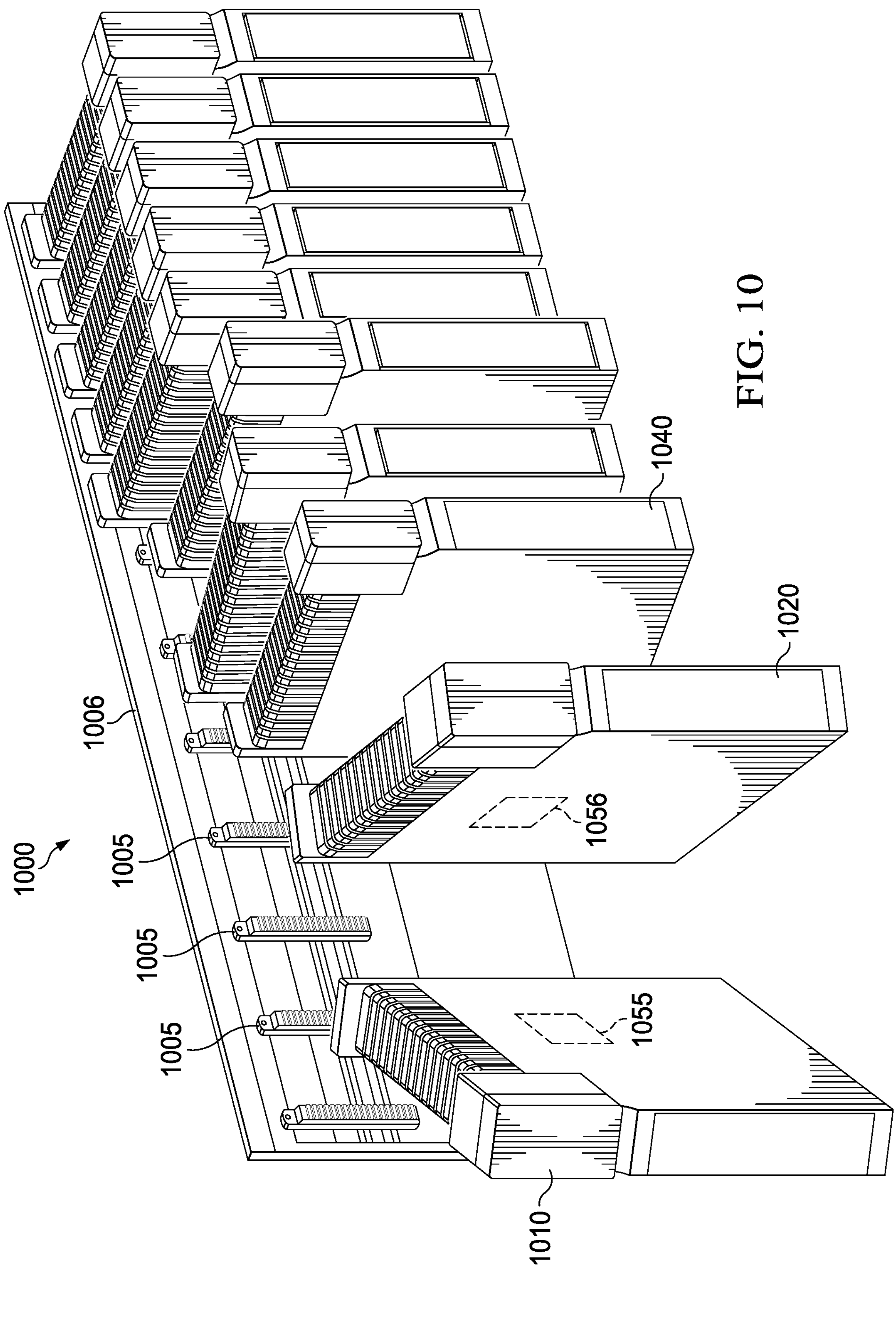



FIG. 10

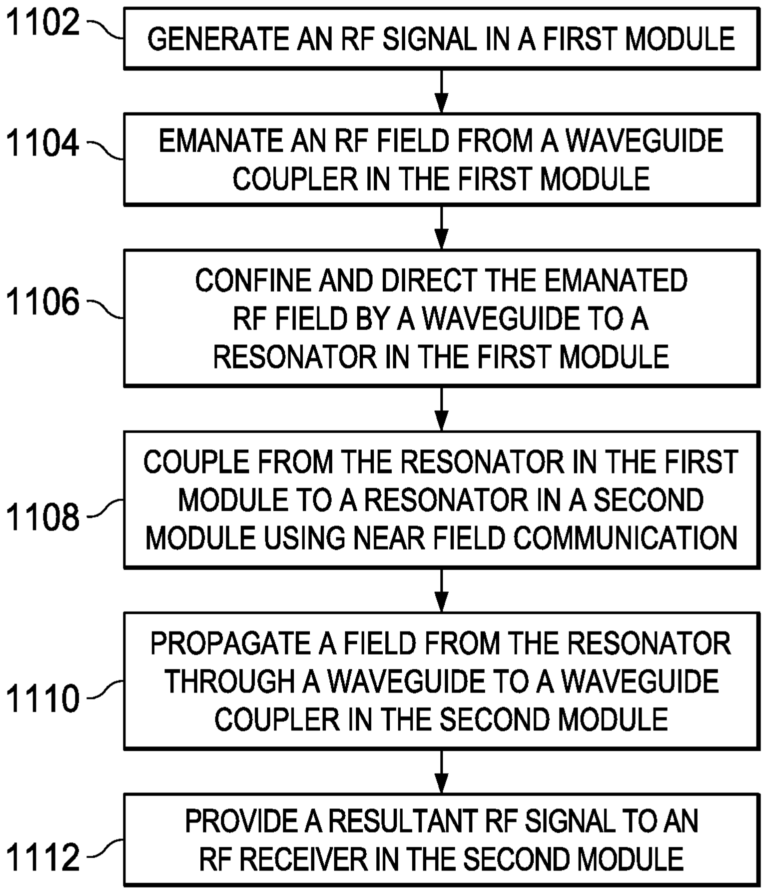

1102
GENERATE AN RF SIGNAL IN A FIRST MODULE
1104
EMANATE AN RF FIELD FROM A WAVEGUIDE COUPLER IN THE FIRST MODULE
1106
CONFINE AND DIRECT THE EMANATED RF FIELD BY A WAVEGUIDE TO A RESONATOR IN THE FIRST MODULE
1108
COUPLE FROM THE RESONATOR IN THE FIRST MODULE TO A RESONATOR IN A SECOND MODULE USING NEAR FIELD COMMUNICATION
1110
PROPAGATE A FIELD FROM THE RESONATOR THROUGH A WAVEGUIDE TO A WAVEGUIDE COUPLER IN THE SECOND MODULE
1112
PROVIDE A RESULTANT RF SIGNAL TO AN RF RECEIVER IN THE SECOND MODULE

FIG. 11

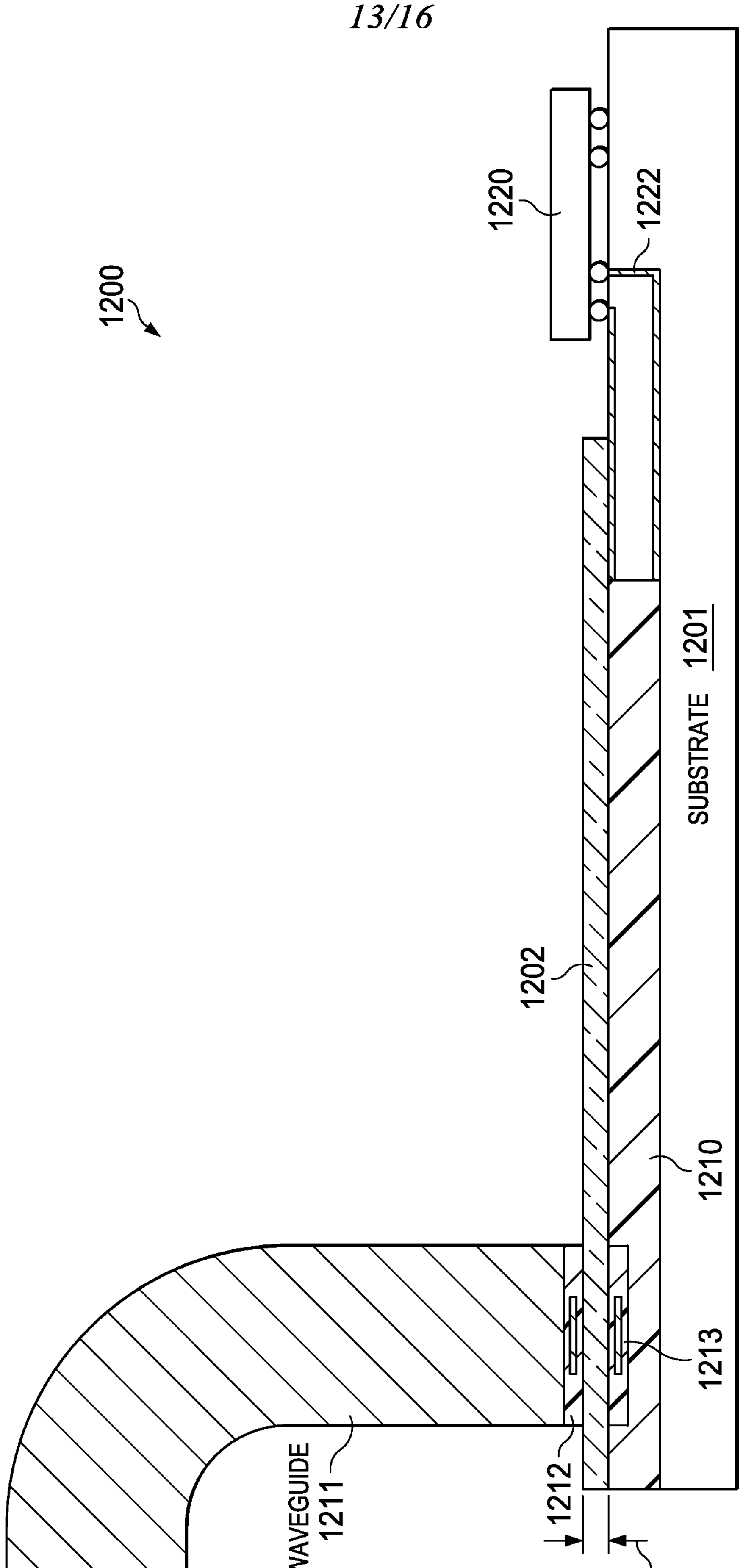

1200
1220
1222
1202
SUBSTRATE 1201
1210
1213
1212
WAVEGUIDE 1211
1204 GAP

FIG. 12

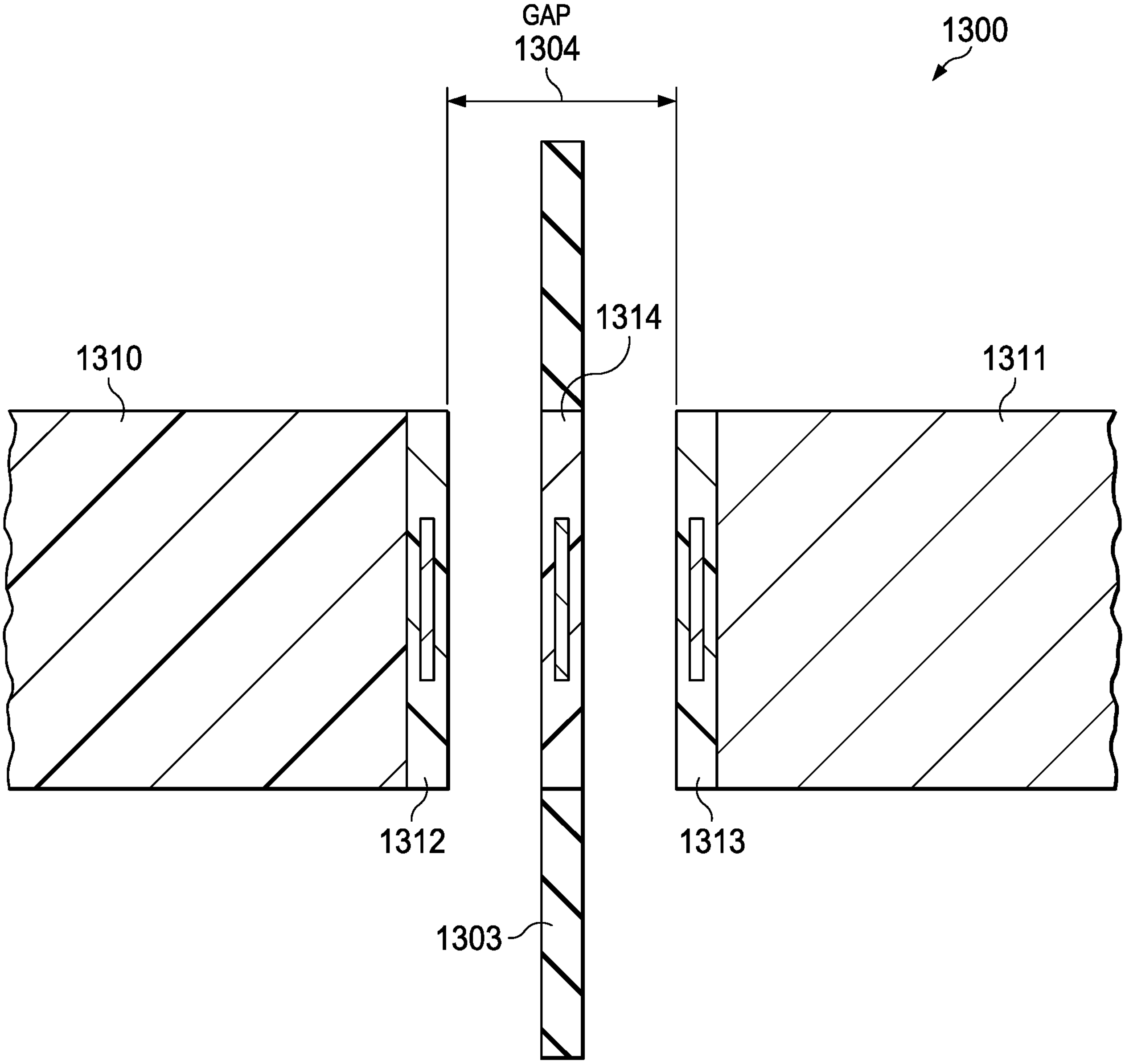



FIG. 13

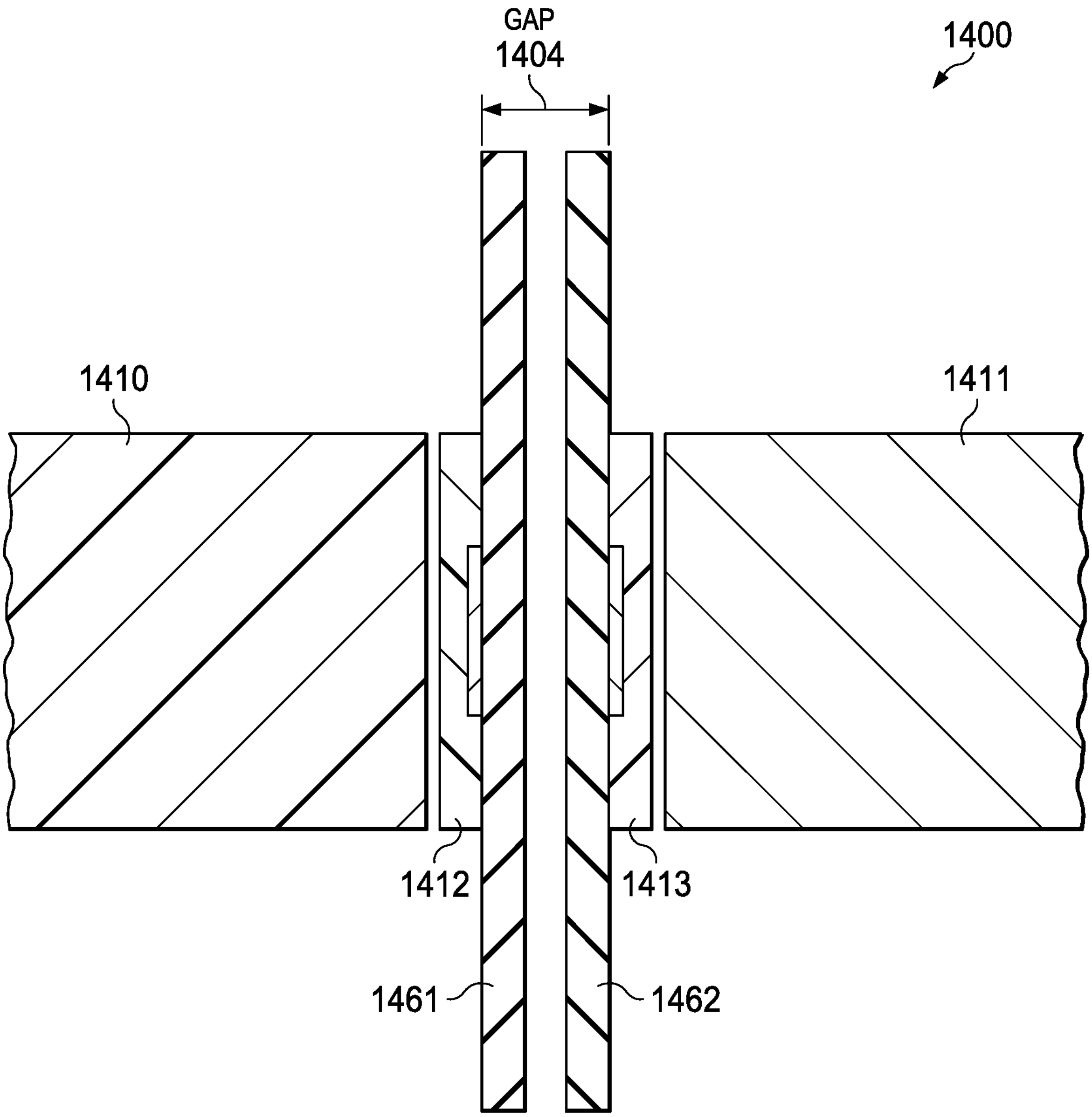



FIG. 14

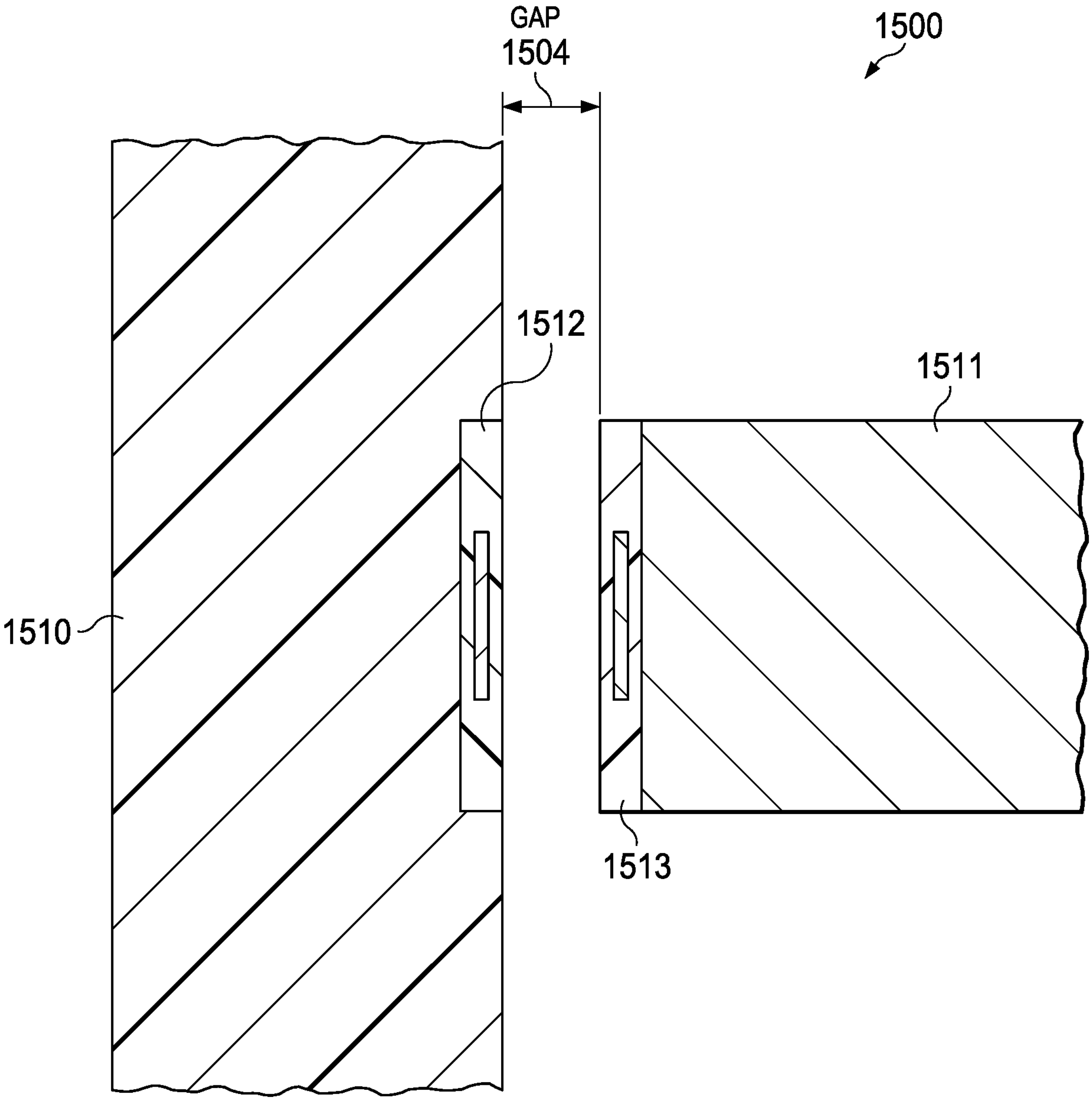



FIG. 15

| INTERNATIONAL SEARCH REPORT | International application No. PCT/US 2017/031196 |
|---|---|

A. CLASSIFICATION OF SUBJECT MATTER

***H04B 5/00*** *(2006.01)*

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)

H04B 5/00, 5/02, H04W 4/00, G06K 19/07, H01P 5/18

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)

PatSearch (RUPTO internal), USPTO, PAJ, Esp@cenet, Information Retrieval System of FIPS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | EP 2833512 A1 (UBE INDUSTRIES) 04.02.2015, fig. 1, 25-27, paragraphs [0013], [0017]-[0018], [0021]-[0025], [0036]-[0040], [0046]-[0053], [0057]-[0067], [0028]-[0040], [0069]-[0079] | 1, 2, 17, 20 |
| Y | | 3-11, 19 |
| A | | 18 |
| Y | EP 2573951 A1 (SONY CORPORATION) 27.03.2013, fig. 4a, 5-6, paragraphs [0030], [0077], [0084], [0087], [0099], [0007]-[0108], [0105]-[0110] | 7-9, 12, 15, |
| A | | 13, 14, 16 |
| Y | US 2002/0132601 A1 (NRD CO LTD) 19.09.2002, paragraphs [0030], [0033]-[0035] | 7-9, 12, 15 |
| Y | US 2649576 A1 (BELL TELEPHONE) 18.08.1953, fig. 12, ref. signs 1120-1231, 1212-1210 | 3 |

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

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

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

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

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

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

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

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

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

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 19 June 2017 (19.06.2017) | 24 August 2017 (24.08.2017) |

| Name and mailing address of the ISA/RU: | Authorized officer |
|---|---|
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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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