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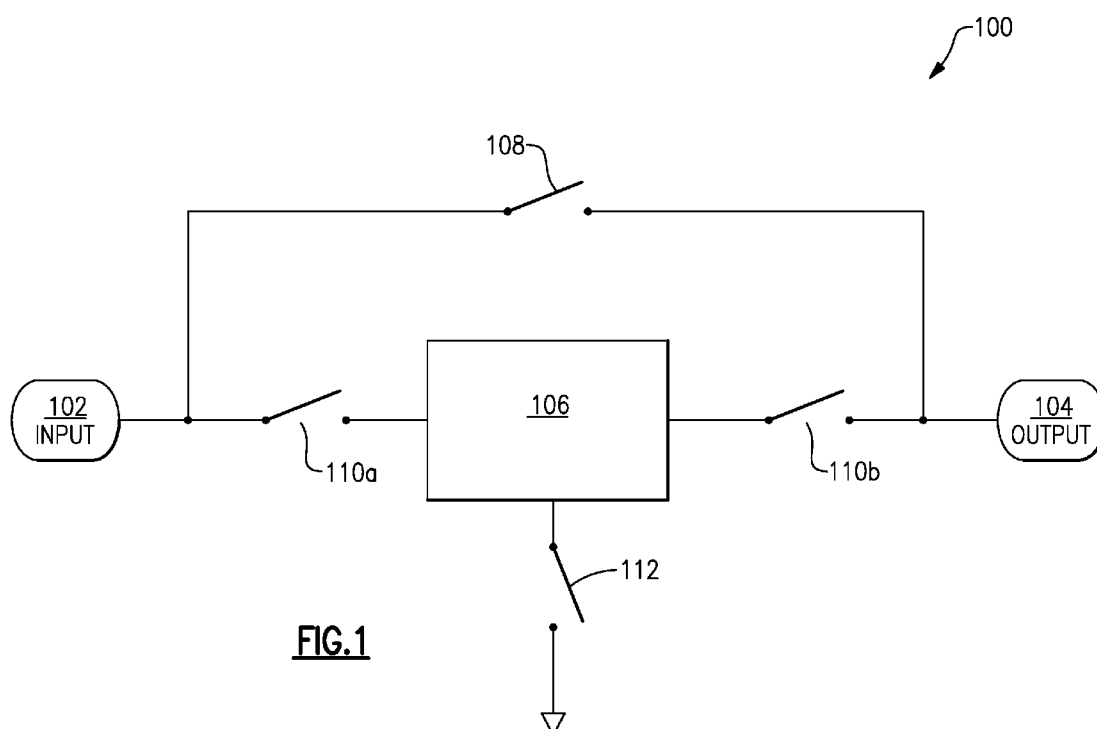


FIG.1

(57) Abstract: An attenuation cell is provided for use in a switched attenuator. The attenuation cell includes an attenuation path that has an input, a first switch, a resistive network, a second switch, and an output. The resistive network provides a desired attenuation from the input to the output. The attenuation cell also includes a bypass path in parallel with the attenuation path with a bypass switch between the input and the output. The attenuation cell also has a shunt switch coupled between the resistive network and a reference node to selectively connect the resistive network to the reference node.

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DIGITAL SWITCHED ATTENUATOR

CROSS REFERENCE TO RELATED APPLICATIONS

5 This application claims the benefit of an earlier filing date under 35 U.S.C. §119(e) and claims the benefit of priority under PCT Article 8, as applicable, to co-pending U.S. Provisional Patent Application No. 62/375,782 filed on August 16, 2016, and to co-pending U.S. Provisional Patent Application No. 62/420,649 filed on November 11, 2016, each of which is incorporated herein by reference in its entirety for all purposes.

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BACKGROUND

Attenuators generally reduce the power of a signal, such as an electromagnetic or a radio frequency signal, without substantially distorting a waveform of the signal. Attenuators may be fixed attenuators that provide a constant level of attenuation or adjustable attenuators
15 that may be configurable between multiple levels of attenuation. Adjustable multi-step attenuators are generally formed by cascading multiple attenuation cells, coupled in series with capacitive elements between each cell. Individual attenuation cells are either selected or bypassed to achieve varying total attenuation levels.

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SUMMARY OF THE INVENTION

Aspects and examples are directed to switched attenuators including directly coupled switched attenuation cells that provide a broad bandwidth, simplified control, and low susceptibility to process variation. The broad bandwidth may be achieved by, for example, direct coupling of one attenuation cell to the next with no intentional capacitive element to
25 couple one cell to the next, thereby making the switched attenuator less frequency dependent and extending the usable bandwidth. This provides an attenuator suitable for a broader range of applications, supporting lower low frequencies and higher high frequencies for a given design than conventional designs. Simplified control may be achieved, for example, by allowing an arbitrary mapping of desired attenuation levels to individual attenuation cells and control

signals. Further, the switched attenuators disclosed herein are less susceptible to process variation due, at least in part, to a design approach to achieve various attenuation levels, within each attenuation cell, using selected circuit architectures and few elemental impedances in various combinations to form overall desired impedance values. This approach results in the overall impedance being consistent despite variation in the elemental impedances brought about by fabrication techniques and process variation.

According to one aspect, an attenuation cell is provided for use in a switched attenuator. The attenuation cell includes an attenuation path having an input, a first switch, a resistive network, a second switch, and an output. The resistive network is electrically disposed between the first switch and the second switch and configured to provide a desired attenuation from the input to the output. The attenuation cell also includes a bypass path in parallel with the attenuation path and having a bypass switch disposed between the input and the output, and a shunt switch coupled between the resistive network and a reference node to selectively connect the resistive network to the reference node.

According to some embodiments, the first switch, the second switch, the bypass switch, and the shunt switch include switching elements that are one of a transistor, a diode, or a microelectromechanical element.

In at least one embodiment, the bypass switch includes a plurality of switching elements equal in number to a combined number of switching elements in the first switch and the second switch. The bypass switch, the first switch, and the second switch may each be formed on a common integrated circuit die. In some embodiments, the bypass switch may have substantially similar parasitic characteristics as the first switch and the second switch combined. The bypass switch, the first switch, and the second switch may include switching elements of all the same type.

In some embodiments, the shunt switch includes at least four switching elements. The shunt switch may include eight switching elements. In some embodiments, the shunt switch includes a number of switching elements selected to reduce the possibility of a breakdown voltage being reached in any of the switching elements.

In embodiments, the resistive network may be a Pi-network, a T-network, a delta network, or a bridged T-network. The resistive network may have a characteristic impedance

of 50 Ohms. The resistive network may include a plurality of resistive elements. Each of the plurality of resistive elements may be identical.

According to other aspects, a module, a coupler, an amplifier, and a communication device are provided that include an attenuation cell according to any of the embodiments described above. A communication device may include a transceiver configured to produce a transmit signal and to receive a receive signal, and may include an antenna and/or a cable coupled to the transceiver and configured to transmit the transmit signal and to receive the receive signal.

According to another aspect, a switched attenuator is provided that includes an input to receive an input signal, an output to provide an attenuated signal, a plurality of attenuation cells directly coupled in series between the input and the output, and a controller coupled to one or more of the plurality of attenuation cells, the controller configured to control an operational state of the one or more of the plurality of attenuation cells.

In at least one embodiment, the operational state of the one or more of the plurality of attenuation cells includes at least one of an attenuation mode, a bypass mode, and an isolated mode. The controller may be configured to control the operational state of one or more of the plurality of attenuation cells to place the switched attenuator into an open circuit mode in which the switched attenuator provides at the output substantially none of the input signal.

In some embodiments, the plurality of attenuation cells includes an input cell, an output cell, and at least one intermediate cell, the at least one intermediate cell being interposed between the input cell and the output cell with no capacitive element therebetween.

In some embodiments, the controller is configured to control the operational state of the one or more of the plurality of attenuation cells to place the switched attenuator into an open circuit mode in which the switched attenuator absorbs a majority of the input signal.

In certain embodiments, the controller may place the switched attenuator into the open circuit mode at least by controlling a first attenuation cell to attenuate a signal received at an input of the first attenuation cell, a level of attenuation being determined by a resistive network of the first attenuation cell, and by controlling a second attenuation cell to reject a signal received at an input of the second attenuation cell by controlling switching elements in the second attenuation cell to be in an open circuit condition.

According to other aspects, a module, a coupler, an amplifier, and a communication device are provided that include a switched attenuator according to any of the embodiments described above. A communication device may include a transceiver configured to produce a transmit signal and to receive a receive signal, and may include an antenna and/or a cable
5 coupled to the transceiver and configured to transmit the transmit signal and to receive the receive signal.

According to another aspect, a switched attenuator is provided that includes an input to receive an input signal, an output to provide an attenuated signal, and a plurality of attenuation cells directly coupled in series between the input and the output. The plurality of attenuation
10 cells having no capacitive coupling element interposed between adjacent attenuation cells. The plurality of attenuation cells includes an input cell coupled to the input and an output cell coupled to the output. Each respective attenuation cell of the plurality of attenuation cells includes an attenuation path having a first switch, a resistive network, and a second switch; a
15 bypass path in parallel with the attenuation path and having a bypass switch; and a shunt switch coupled between the resistive network and a reference node to selectively connect the resistive network to the reference node.

In some embodiments, the bypass switch of each respective attenuation cell includes a plurality of switching elements equal in number to a combined number of switching elements in the first switch and the second switch of the respective attenuation cell. The bypass switch
20 of each respective attenuation cell may have a substantially similar parasitic characteristic to a combined parasitic characteristic of the first switch and the second switch of the respective attenuation cell. In some examples, all the switching elements of the bypass switch, the first switch, and the second switch of the respective attenuation cell are of a same type.

In certain embodiments, each of the plurality of attenuation cells is identical except for
25 the resistive network included in the respective attenuation cell. Each resistive network included in the respective attenuation cell may include a plurality of identical resistive elements.

Some embodiments include a controller coupled to one or more of the plurality of attenuation cells, the controller configured to control an operational state of the one or more of
30 the plurality of attenuation cells.

Still other aspects, examples, and advantages of these exemplary aspects and examples are discussed in detail below. Examples disclosed herein may be combined with other examples in any manner consistent with at least one of the principles disclosed herein, and references to “an example,” “some examples,” “an alternate example,” “various examples,” “one example” or the like are not necessarily mutually exclusive and are intended to indicate that a particular feature, structure, or characteristic described may be included in at least one example. The appearances of such terms herein are not necessarily all referring to the same example.

BRIEF DESCRIPTION OF THE DRAWINGS

Various aspects of at least one example are discussed below with reference to the accompanying figures, which are not intended to be drawn to scale. The figures are included to provide illustration and a further understanding of the various aspects and examples, and are incorporated in and constitute a part of this specification, but are not intended as a definition of the limits of the invention. In the figures, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every figure. In the figures:

FIG. 1 is a schematic circuit diagram of an example attenuation cell;

FIGS. 2A-2B are schematic circuit diagrams of examples of digital switches;

FIGS. 3A-3C are schematic circuit diagrams of examples of resistive networks;

FIG. 4 is a schematic circuit diagram of an example resistive network;

FIG. 5 is a schematic circuit diagram of the example attenuation cell of FIG. 1 including example digital switches of FIG. 2 and the example resistive network of FIG. 4;

FIG. 6 is a block diagram of a multi-cell digital switched attenuator;

FIG. 7 is a block diagram of an example packaged module including a digital switched attenuator;

FIGS. 8A-8F are block diagrams of example coupler modules including a digital switched attenuator;

FIGS. 9A-9C are block diagrams of example amplifier modules including a digital switched attenuator; and

FIG. 10 is a block diagram of an example communication device that may include one or more digital switched attenuators.

DETAILED DESCRIPTION

5 Aspects of the present disclosure are directed to switched attenuators including directly coupled switched attenuation cells that provide a broad bandwidth, simplified control, and low susceptibility to process variation. The switched attenuators disclosed herein are capable of providing multiple levels of attenuation through a series of cells. Attenuation levels may be selected by, for example, switchably connecting in series one or more attenuation cells of
10 various attenuation levels. Thereby, the total attenuation of the attenuator may be altered resulting in different levels of attenuation. Further, the switched attenuator may include connection topologies that remove the need for direct current (DC) blocking capacitors and thereby reduce the reactance of the overall circuit to maximize the effective bandwidth, e.g., extend the low frequency range and improve high frequency roll-off, to provide a broad range
15 of high accuracy linear attenuation levels across a wide spectrum of frequencies. Additionally, the switched attenuator may include attenuation networks (e.g., resistor networks) that compensate for deviations introduced by, for example, manufacturing variation in the fabrication of resistive elements.

It is to be appreciated that examples of the methods and apparatuses discussed herein
20 are not limited in application to the details of construction and the arrangement of components set forth in the following description or illustrated in the accompanying drawings. The methods and apparatuses are capable of implementation in other examples and of being practiced or of being carried out in various ways. Examples of specific implementations are provided herein for illustrative purposes only and are not intended to be limiting. Also, the
25 phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use herein of “including,” “comprising,” “having,” “containing,” “involving,” and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. References to “or” may be construed as inclusive so that any terms described using “or” may indicate any of a single, more than one,
30 and all of the described terms. Any references to front and back, left and right, top and bottom, upper and lower, and vertical and horizontal are intended for convenience of description, not to

limit the present systems and methods or their components to any one positional or spatial orientation.

FIG. 1 illustrates an example attenuation cell 100 constructed to receive an input signal and provide an output signal. As illustrated in FIG. 1, the attenuation cell 100 receives the input signal at an attenuation cell input 102 and provides the output signal at an attenuation cell output 104. It is appreciated that the attenuation cell 100 may be symmetrical and, thereby, receive the input signal at either port and still function in the same manner.

The attenuation cell 100 includes a resistive network 106 coupled in parallel with a bypass switch 108 and coupled to the signal path by one or more attenuation switches 110. The resistive network 106 includes a shunt terminal connected to a shunt switch 112. Depending upon the resistive network 106 and in various embodiments, additional shunt terminals may be connected to additional shunt switches.

The attenuation cell 100 may operate in an attenuation mode by closing the attenuation switches 110a, 110b (i.e., conducting), and opening the bypass switch 108 (i.e., non-conducting), resulting in an input signal being directed through the resistive network 106, which will reduce a power level of the input signal by action of the resistive network 106. In embodiments, the shunt terminal of the resistive network 106 is coupled to ground through the shunt switch 112 in a closed (conducting) state.

The attenuation cell 100 may operate in a bypass mode by closing bypass switch 108 to bypass the resistive network 106 and provide an output signal that is substantially the same as the input signal.

In the example illustrated in FIG. 1, there are two attenuation switches 110 and one shunt switch 112 connected to the resistive network 106. The attenuation switches 110a, 110b connect the resistive network 106 to the attenuation cell input 102 and the attenuation cell output 104. The shunt switch 112 connects a third terminal of the resistive network 106 to a reference node, which is a ground reference potential in the example of FIG. 1 but could be an alternate potential or a floating potential.

The attenuation switches 110 and shunt switch 112 isolate the resistive network 106 from the remainder of the attenuation cell 100 when open (i.e., non-conducting), and thereby remove the resistive network 106 from the signal path when the attenuation cell 100 is in bypass mode or in an isolated (i.e., open circuit) mode. Further, by isolating the resistive

network 106 from the signal path, parasitic losses caused by the resistive network 106 are reduced when operating in bypass mode.

The bypass switch 108, the attenuation switches 110, and the shunt switch 112 may be constructed in a variety of manners depending upon the particular implementation. Any of the bypass switch 108, the attenuation switches 110, and the shunt switch 112 may be implemented as a single transistor or other component capable of being selectively placed in a conducting state or a non-conducting state. A transistor, such as a Field Effect Transistor (FET), a Bipolar Junction Transistor (BJT), or others, may be a suitable component. Additionally, in embodiments, other elements may be used, such as Microelectromechanical System (MEMS) Switches, diodes, diode connected transistors, PIN diodes, etc. In embodiments, multiple components may be connected together to form any of the bypass switch 108, the attenuation switches 110, and the shunt switch 112.

In FIGS. 2A-2B, examples of a switch 200 are constructed by connecting a plurality of Field Effect Transistors $T_1 - T_n$ in series. The plurality of series-connected transistors, as opposed to a single transistor, may provide additional isolation when off (non-conducting) than may be provided over fewer transistors or by only one transistor. Additionally, a plurality of transistors in series may accommodate a higher input power as the signal voltage level is distributed across more transistors, reducing the possibility of voltage breakdown in any of the transistors, when necessary. Also shown in FIGS. 2A-2B is that the transistor gates are tied together to form a control input such that a control voltage applied to any of the gates is effectively applied to all the gates, thereby controlling the conducting or non-conducting state of the transistors. Additionally as shown, the gates of the individual transistors may be tied together via gate resistances, either as individual gate resistances, such as in FIG. 2A, or as additive series gate resistances, as in FIG. 2B, or any combination of these or other arrangements. Additionally, in embodiments, two or more of the gates may be directly electrically tied to each other without a resistance between them. Any of the bypass switch 108, the attenuation switches 110, and the shunt switch 112 may be formed from the example switch 200 or variations thereof.

The attenuation switches 110 and other elements may themselves attenuate the input signal in addition to the attenuation applied by the resistive network 106 while in attenuation mode. Accordingly, the attenuation provided by the resistive network 106 may be designed to

be slightly lower than the total desired attenuation to compensate for attenuation introduced by other elements, such as the switches. An aspect of at least one embodiment includes matching, or balancing, the impact of the bypass switch 108 with the impact of the attenuation switches 110 and/or shunt switch 112 so that the difference in attenuation produced by the attenuation mode as compared to the bypass mode is due solely to the resistive network 106. In other words, when the attenuation cell 100 is switched from bypass mode to attenuation mode, or vice versa, a precise change in the attenuation level will result and is due substantially solely to the attenuation of the resistive network 106.

As described above, the attenuation cell 100 may include a resistive network 106 to attenuate the input signal when the attenuation cell 100 is in the attenuation mode of operation. Various types of resistive networks 106 may be employed depending upon the particular implementation. For example, the resistive network 106 may include a number of options for an attenuator network or circuit topology, as described further below, and elemental values, such as resistance values, may be selected to provide any of numerous attenuation levels, such as, for example, $\frac{1}{2}$ dB, 1dB, 2dB, 3dB, 4dB, 6dB, 9dB, etc.

In embodiments, multiple attenuation cells 100 are coupled together, e.g., in series, as in the digital switched attenuator 600 of FIG. 6, and may provide a variable attenuation level by controlling the individual attenuation cells 100 to be in attenuation mode or in bypass mode as discussed above. Further, the digital switched attenuator 600 may be open-circuited by controlling at least one attenuation cell 100 to be in an isolated mode, i.e., open-circuited, by having its bypass switch 108 and at least one of its attenuation switches 110a or 110b in an open (non-conducting) state, so that no signal path is formed between the attenuation cell input 102 and the attenuation cell output 104.

Further, individual attenuation cells 100 include a resistive network 106 that may be a fixed attenuator providing a single constant level of attenuation, a multi-step attenuator configurable between a pre-defined set of attenuation levels, or a variable attenuator that is configurable within a continuous range of attenuation levels.

FIGS. 3A-3C illustrate examples of fixed attenuator circuits suitable to employ as resistive network 106. FIG. 3A illustrates a T-network circuit topology, FIG. 3B illustrates a Pi-network circuit topology, and FIG. 3C illustrates a Bridged T-network circuit topology. The resistive network 106 may be implemented as one or more of the circuit topologies shown in

FIGS. 3A-3C, or may be variations or equivalent circuits of the circuit topologies shown in FIGS. 3A-3C, or may be implemented as other circuit topologies. The impedance elements of the circuit topologies shown in FIGS. 3A-3C, e.g., impedances R_1 , R_2 , and R_3 , may be implemented as pure resistances as shown or may include inductive or capacitive elements in various embodiments.

In at least one embodiment, the bridged T-network of FIG. 3C is used as the model for a resistive network 106. The bridged T-network of FIG. 3C includes two impedances R_3 connected in series between the input and the output terminals, a shunt impedance R_1 coupled between the two series connected impedances R_3 and a third terminal, and a bridge impedance R_2 coupled between the input and the output, in parallel with the series connected impedances R_3 . The values for the impedances R_1 , R_2 , and R_3 may be determined based on the relationships illustrated in equations (1) below given a desired attenuation level A in dB and a desired characteristic impedance Z_0 :

$$R_1 = \frac{Z_0}{\sqrt{10^{\frac{A}{10}} - 1}} \quad \left| \quad R_2 = Z_0 * \left(\sqrt{10^{\frac{A}{10}} - 1} \right) \quad \right| \quad R_3 = Z_0 \quad (1)$$

Table 1 illustrates example values for the impedances R_1 , R_2 , and R_3 to achieve various attenuation steps in a bridged-T resistive network 106 as described above with reference to FIG. 3C, using equations (1) and assuming a desired characteristic impedance $Z_0 = 50 \Omega$.

Total Attenuation Step	Calculated R_1 Shunt Values	Calculated R_2 Bridge Values	R_3 Values (= Z_0)
½ dB	843.8 Ω	2.96 Ω	50 Ω
1 dB	409.8 Ω	6.10 Ω	50 Ω
2 dB	193.1 Ω	12.95 Ω	50 Ω
3 dB	121.2 Ω	20.63 Ω	50 Ω
4 dB	85.49 Ω	29.24 Ω	50 Ω
6 dB	50.24 Ω	49.76 Ω	50 Ω
9 dB	27.50 Ω	90.92 Ω	50 Ω

Table 1

The impedances R_1 , R_2 , and R_3 for each attenuation cell 100, in relation to the resistive network 106 of FIG. 3C and values of Table 1, may be established by a variety of methods depending upon the particular implementation. For example, with reference to FIG. 4, multiple impedances connected in parallel or in series may replace one or more of the single impedances R_1 , R_2 , and R_3 . This approach may be advantageous because it may avoid the use of small impedance values, which generally are more difficult to manufacture with tight tolerances and/or may require more space. With reference to Table 1, attenuators with low attenuation levels, e.g., $\frac{1}{2}$ dB or 1 dB, include relatively high values for R_1 and relatively low values for R_2 . Accordingly, the resistive network 106 of FIG. 4 is shown with series-connected impedances R_{1a} , R_{1b} , and R_{1c} that yield an additive total value of R_1 , allowing the component values of R_{1a} , R_{1b} , and R_{1c} individually to be smaller while achieving a larger value for R_1 overall. Comparably, the resistive network 106 of FIG. 4 is shown with parallel-connected impedances R_{2a} , R_{2b} , and R_{2c} that yield a value of R_2 lower than any of R_{2a} , R_{2b} , and R_{2c} individually. This approach allows fabrication of impedances R_1 and R_2 (for example, in an integrated circuit) from multiple individual impedances (e.g., R_{1a} , R_{1b} , R_{1c} , R_{2a} , R_{2b} , and R_{2c}) that may allow for more precise and/or more consistent impedances R_1 and R_2 in the face of manufacturing process variation.

For example, for a desired characteristic impedance $Z_0 = 50 \Omega$, a manufacturing process may be capable of reliably producing a resistive impedance of 50Ω , which may reliably produce the impedance R_3 for any attenuation level of the attenuation cells 100, as shown in Table 1. With reference to the 1 dB values from Table 1, the impedance R_1 is approximately eight times (8x) the value of impedance R_3 , and the impedance R_2 is approximately one-eighth ($\frac{1}{8} \times$) the value of impedance R_3 . Using the circuit topology of FIG. 4, the impedances R_1 and R_2 of FIG. 3C may be more reliably produced for a 1 dB attenuation cell by forming R_1 from 8 resistors of 50Ω each connected in series and forming R_2 from 8 resistors of 50Ω each connected in parallel. More generally, fabricating multiple 50Ω resistors in parallel or in series may be more accurate than fabricating individual resistors of, for example, 25Ω or less and 100Ω or more. Additionally, and as in the 1 dB example, the desired impedances R_1 and R_2 may not be exact integer values of R_3 or another component impedance, but manufacture of multiple component impedances of similar or approximately the same values, though not exactly the

same value, will generally yield a more consistent set of equivalent impedances, resulting in a resistive network 106 design that is more immune to process variation during manufacture.

While the resistive network 106 of FIG. 4 is shown with three component impedances R_{1a} , R_{1b} , and R_{1c} contributing to impedance R_1 and three component impedances R_{2a} , R_{2b} , and R_{2c} contributing to impedance R_2 , it is understood that the example discussed, and various embodiments, may include more or fewer component impedances for any particular impedance and any particular design of the resistive network 106. In particular, a resistive network 106 may be designed for virtually any desired attenuation level from virtually any available set of component impedances R by applying the aspects and relationships described above.

In at least one embodiment of a resistive network 106, the impedances R_1 , R_2 , and R_3 are designed to be resistances, as shown, without any intentional reactive component. Accordingly, such a resistive network 106 is substantially frequency independent.

FIG. 5 illustrates an embodiment of an attenuation cell 100 including an attenuation cell input 102, an attenuation cell output 104, a resistive network 106, a bypass switch 108, attenuation switches 110, a shunt switch 112, a bypass control line 508, and an attenuation control line 510. In the example embodiment of FIG. 5, the bypass switch 108, the attenuation switches 110, and the shunt switch 112 each include one or more Field Effect Transistors (FETs). The bypass switch 108 includes two series-connected FETs with channel gates coupled to the bypass control line 508 through an impedance. The channel gates of the bypass switch 108 FETs receive a signal from the bypass control line 508 that places the bypass switch 108 FETs in a conducting state or a non-conducting state. When the bypass switch 108 is in a conducting state, e.g., enabled by the bypass control line 508, the signal path through the attenuation cell 100 is from the attenuation cell input 102 through the bypass switch 108 to the attenuation cell output 104, effectively bypassing the resistive network 106. In this manner, the attenuation cell 100 is in a bypass mode and allows a signal to pass from the attenuation cell input 102 to the attenuation cell output 104 with little to no attenuation. In embodiments, the bypass switch 108 may include more or fewer switching elements, e.g., more or fewer FETs, BJT's, MEMS switches, diodes, etc.

The attenuation switches 110a, 110b are series-connected with two terminals of the resistive network 106, between the attenuation cell input 102 and the attenuation cell output 104, respectively, and are part of an attenuation path from the attenuation cell input 102 to the

attenuation cell output 104. In the example embodiment of FIG. 5, the attenuation switches 110a and 110b are each a single FET. The shunt switch 112 is a shunt connection between the third terminal of the resistive network 106 and a reference node, such as ground. In the example embodiment of FIG. 5, the shunt switch 112 includes eight (8) FETs connected in series. In this embodiment, the number of FETs in the shunt switch 112 may vary and may be selected to accommodate particular signal voltages along the signal path from the attenuation cell input 102 to the attenuation cell output 104. One design criteria may include a number of FETs to ensure that when the shunt switch 112 is controlled to be in an off (non-conducting) state, enough of the FETs will remain in a non-conducting state to maintain the shunt switch 112 overall in a non-conducting state even as voltages in the FET channels may vary due to a signal traversing from the attenuation cell input 102 to the attenuation cell output 104. Additionally, the number of FETs in the shunt switch 112 may be chosen to provide for varying applications or other operational requirements.

In some embodiments, each FET of the attenuation switches 110 and the shunt switch 112 has a channel gate coupled to an attenuation control line 510 through impedances. The channel gates of the attenuation switches 110 and the shunt switch 112 FETs receive a signal from the attenuation control line 510 that places the attenuation switches 110 and the shunt switch 112 in a conducting state or a non-conducting state. When the attenuation switches 110 and the shunt switch 112 are in a conducting state, e.g., enabled by the attenuation control line 510, and when the bypass switch 108 is in a non-conducting state, e.g., not enabled by the bypass control line 508, the attenuation cell 100 is in an attenuation mode wherein the signal path through the attenuation cell 100 is from the attenuation cell input 102, through the attenuation switch 110a, through a portion of the resistive network 106, through the attenuation switch 110b, and to the attenuation cell output 104. A portion of the signal energy is also shunted to the reference node through a portion of the resistive network 106, e.g., through shunt impedance R_1 and the shunt switch 112. In this manner, the attenuation cell 100 is in an attenuation mode wherein a signal received at the attenuation cell input 102 is attenuated by the resistive network 106 and an attenuated portion of the signal is provided at the attenuation cell output 104.

In various embodiments, any of the bypass switch 108, the attenuation switches 110, and the shunt switch 112, may be constructed of other transistor types, such as Bipolar Junction

Transistor (BJT's), or other suitable switching structures, such as MEMS switches or diode arrangements, and each may include more or fewer transistors or switching elements and may be controlled by other arrangements.

In at least one embodiment, the bypass switch 108 and the attenuation switches 110 may be matched to have substantially equivalent effect on a signal whether the attenuation cell 100 is in bypass mode or attenuation mode, yielding a more consistent and predictable variation between the two modes. In at least one embodiment, the bypass switch 108 may be configured to have a parasitic effect substantially equivalent to the total parasitic effects of the attenuation switches 110. The beneficial result is the difference in attenuation between bypass mode and attenuation mode is substantially solely the result of the resistive network 106 because there are minimal, if any, other differences between the bypass path and the attenuation path.

For example, in at least one embodiment, the number and type of switching components, e.g., FETs, included in the bypass path and the attenuation path are equal. For example, as in the attenuation cell of FIG. 5, there are two FETs in the bypass path (e.g., the signal path when the bypass switch 108 is conducting) and two FETs in the attenuation path (e.g., the signal path when the attenuation switches 110 are conducting). Further, the switching components, e.g., FETs, in the bypass switch 108, the attenuation switches 110, and the shunt switch 112, may all be of the same type, variety, and design. Utilizing a matching number and type of switching components results in the switching components having substantially equivalent effect on a signal whether the attenuation cell 100 is in bypass mode or attenuation mode, yielding a more consistent and predictable variation between the two modes, i.e., the difference in attenuation between the two modes is substantially solely due to the resistive network 106 as there are minimal, if any, other differences between the bypass path and the attenuation path.

In some embodiments, the attenuation cell 100 may include a control inverter 512 that couples the bypass control line 508 to the attenuation control line 510 in a manner that holds the bypass control line 508 signal to be the opposite of the attenuation control line 510 signal. For example, with the control inverter 512 optionally included as shown in FIG. 5, a control signal only need be received at the attenuation control line 510 and the control applied to the bypass switch 108 will automatically be the opposite of the control applied to the attenuation switches 110. In other words, as optionally arranged in FIG. 5, the bypass switch 108 will

always be off when the attenuation switches 110 and the shunt switch 112 are controlled to be on, and the bypass switch 108 will always be on when the attenuation switches 110 and the shunt switch 112 are controlled to be off. In other embodiments, a control inverter 512 may be included in the reverse orientation, such that the attenuation cell 100 is controlled by a bypass control line 508 signal, wherein the attenuation switches 110 and the shunt switch 112 will automatically receive a control signal that is the opposite of the bypass control line 508 signal. Providing a control inverter 512 in either manner provides a benefit of only needing one control input from the exterior of the attenuation cell 100. In other embodiments, as previously described, a control inverter 512 may not be included so that the bypass control line 508 and the attenuation control line 510 may be operated independently.

The above description of the operation and arrangement of the bypass switch 108, the attenuation switches 110, and the shunt switch 112, identifies two modes of the attenuation cell 100, a bypass mode and an attenuation mode. Additionally, the attenuation cell 100 may be controlled to be in an isolated mode by controlling at least the bypass switch 108 and at least one of the attenuation switches 110a, 110b to be non-conducting (i.e., open, or off) at the same time. In the isolated mode effectively none of any signal received at the attenuation cell input 102 is provided at the attenuation cell output 104. While a minimum of the bypass switch 108 and one of the attenuation switches 110 must be off for the attenuation cell 100 to be in an isolated mode, it may be desirable and typical for all switching elements to be off (non-conducting) to produce the maximum isolation between the attenuation cell input 102 and the attenuation cell output 104 when in isolated mode.

The case of the bypass switch 108, the attenuation switches 110, and the shunt switch 112 all being in a conducting state (i.e., closed, or on) is not a typical mode in which to operate the attenuation cell 100, but such a condition would generally be substantially equivalent to the bypass mode because a majority of any signal energy received at the attenuation cell input 102 will tend to follow a signal path through the conducting bypass switch 108 to the attenuation cell output 104. The fact of the attenuation switches 110 being in a conducting state at the same time will generally cause additional parasitic losses resulting in a less effective bypass mode than otherwise would be the case.

While the example embodiment of FIG. 5 illustrates common control of all transistors of the attenuation switches 110 and the shunt switch 112, and common control of all the

transistors of the bypass switch 108, in various embodiments control of the bypass switch 108, the attenuation switches 110, the shunt switch 112, or of individual transistors or switching elements thereof, may be arranged differently. In one such embodiment, one or more of the transistors (or switching elements) of the shunt switch 112 may be controlled separately from the series attenuation switches 110a, 110b. Accordingly, some embodiments support a hybrid attenuation mode wherein the attenuation cell input 102 may be coupled to the attenuation cell output 104, through the resistive network 106, via the attenuation switches 110a and 110b, each in a conducting state, while the shunt switch 112 remains in a non-conducting state. In such a scenario, the attenuation cell 100 may provide a different attenuation level than when the shunt switch 112 is in a conducting state.

The three basic modes of operation, isolated, bypass, and attenuation, are summarized in Table 2 below.

Mode	Bypass Switch 108	Attenuation switches 110a, 110b	Shunt switch 112
Bypass Mode	On	Off	Off
Isolated Mode	Off	Off	Off
Attenuation Mode	Off	On	On

Table 2

As illustrated in Table 2, whenever the bypass switch 108 is in a conducting state (on), the attenuation cell 100 is effectively in a bypass mode. The bypass switch 108 in a conducting state forms a substantially direct coupling from the attenuation cell input 102 to the attenuation cell output 104 with substantially no attenuation. Parasitic losses due to the resistive network 106 and the attenuation switches 110 are minimized by having the attenuation switches 110 and the shunt switch 112 in a non-conducting (off) state. In various embodiments, the arrangement may be different, and the bypass mode may be more or less effective based upon the state of the attenuation switches 110 and the shunt switch 112.

As further illustrated in Table 2, when all the switches are off (non-conducting), the attenuation cell 100 is in an isolated mode where substantially none of a signal received at the attenuation cell input 102 is provided at the attenuation cell output 104.

As finally illustrated in Table 2, when the bypass switch 108 is off (non-conducting) and the attenuation switches 110 and the shunt switch 112 are on (conducting), an attenuated portion of a signal received at the attenuation cell input 102 is provided at the attenuation cell output 104. The signal strength at the attenuation cell output 104 is reduced from that at the attenuation cell input 102 by the designed attenuation level of the resistive network 106 as previously described.

In various embodiments, the resistive network 106 used in the attenuation cell 100 may be of varying designs to accommodate changing operational parameters or applications, including attenuation levels and impedance matching. For example, the impedances may be of varying values, as previously discussed, and the resistive network 106 may be of differing circuit design, such as a T, Pi, Delta, bridged, or alternate arrangement. In various embodiments, the resistive network 106 used in the attenuation cell 100 may be a variable, adjustable, or tunable attenuator, or a multi-step attenuator capable of being further controlled to provide various levels of attenuation.

A multi-cell digital switched attenuator, such as shown in FIG. 6, may include numerous attenuation cells 100 connected in series, and a controller 612 that will control the bypass switch 108, the attenuation switches 110, and the shunt switch 112 of one or more of the attenuation cells 100, to switchably select one or more attenuation cells 100 to be in an attenuation mode, a bypass mode, or an isolated mode. The individual attenuation cells 600 may be designed to provide identical attenuation levels or may be designed to provide different attenuation levels. Higher attenuations are achieved by selecting additional attenuation cells 100 in attenuation mode (in series) to attenuate the signal. Accordingly, a set of attenuation cells 100 may be selected with attenuation levels such that any desired attenuation level is achievable by selectively switching the various series-connected attenuation cells 100 between bypass mode and attenuation mode. In certain embodiments, the attenuation cells 600 may all be of identical design, differing only in the resistive values of their individual resistive networks 606, to provide differing attenuation levels. Additionally, even for differing attenuation levels, all of the attenuation cells 600 may have identical resistor components, varying only in number of the resistor components connected in series and/or parallel, as discussed above. Accordingly, various signal characteristics of each attenuation cell 600 may be substantially similar, varying substantially only by a level of attenuation provided.

FIG. 6 is a block diagram of a digital switched attenuator 600 including an input 602, an output 604, and a plurality of attenuation cells 100 DC coupled in series between the input 602 and the output 604. It is appreciated that each attenuation cell 100 has an attenuation cell input 102 and an attenuation cell output 104 that may be serially connected to adjacent attenuation cells 100. The attenuation cell outputs may be coupled to the adjacent attenuation cell inputs without a capacitive coupling element. The attenuation cells 100a, 100n at the terminal ends of the digital switched attenuator 600 provide the input 602 and the output 604, respectively, of the overall digital switched attenuator 600. The digital switched attenuator 600 may include any number of attenuation cells 100, depending upon operational parameters and varying application needs, and each individual attenuation cell 100 may be of any individual attenuation level. By controlling the operational state of each of the attenuation cells 100, i.e., to be in attenuation mode, bypass mode, or isolated mode, any of various total attenuation levels may be achieved. Various embodiments may have any number of, and any attenuation levels of, attenuation cells 100 arranged in any relative position to one another.

The digital switched attenuator 600 of FIG. 6 also includes a controller 612 that controls the bypass control lines 508 carrying control signals to the attenuation cells 100 and the attenuation control lines 510 carrying control signals to the attenuation cells 100. The controller 612 controls the bypass and attenuation signals to the attenuation cells 100, thereby controlling the operational states of the attenuation cells 100 and therefore the total attenuation applied to a signal received at the input 602. The controller 612 may receive instructions via a communication interface from another component, to determine the desired operation state of the digital switched attenuator 600, or the controller 612 may have various sensors, such as an output power sensor, and the controller 612 may be programmed or instructed to maintain a certain output power level, for example. Other components that may communicate with the controller 612 may include, for example, a baseband transceiver controller, an amplifier controller, a coupler controller, a frequency band controller, a controller for a radio frequency front-end module, and the like.

Still referring to FIG. 6, the digital switched attenuator 600 is capable of passing a signal substantially unattenuated (0 dB attenuation) when the controller 612 enables a bypass mode in all of the attenuation cells 100 by controlling the bypass switch 108 of each attenuation cell 100 to be in an on (conducting) state. In this state, a signal received at the input 602 will

propagate through the bypass switches 108 of all the attenuation cells 100 and be provided at the output 604 substantially unattenuated.

By controlling signals on the bypass control lines 508 and the attenuation control lines 510, and thereby controlling the conducting or non-conducting states of the bypass switches 108 and the attenuation switches 110, respectively, of each attenuation cell 100, the digital switched attenuator 600 of FIG. 6 may be placed in condition to provide any attenuation level desired from 0 dB (i.e., all attenuation cells 100 in bypass mode) to its maximum attenuation level (i.e., all attenuation cells 100 in attenuation mode), in increments based upon the possible combinations of bypass modes and attenuation modes among all of the attenuation cells 100.

Various embodiments may have more or fewer attenuation cells 100, or a different arrangement of attenuation cells 100, or differing incremental attenuation levels, or may have attenuation levels of the attenuation cells 100 chosen, designed, or arranged such that all possible intermediate incremental values are achievable, or may be arranged so only a particular set of attenuation values is achievable without all possible intermediate incremental values being achievable. The controller 612 may be configured to accept a range of binary input values and map them to a particular total attenuation level by controlling signals on the bypass control lines 508 and the attenuation control lines 510. In certain embodiments, the controller 612 may be programmable or otherwise configurable. Other suitable controllers may be provided in certain embodiments.

The digital switched attenuator 600 of FIG. 6 may substantially reject, or block, a signal received at the input 602 to provide substantially no signal at the output 604 (i.e., substantially infinite attenuation), by placing one or more of the attenuation cells 100 into isolated mode. One approach includes placing all the attenuation cells 100 into isolated mode. A better approach may be to place a number of the attenuation cells 100 into attenuation mode, particularly those near the input 602, and perhaps those near the output 604, while placing the more central attenuation cells 100 in isolated mode. The benefit of leaving periphery attenuation cells 100 in attenuation mode is that any signal received at the input 602 (or at the output 604) is attenuated by the attenuation cells 100 encountered by the signal before reaching an isolated attenuation cell, thus maintaining an impedance match at the input 602 and the output 604 and reducing any reflected portion of the received signal. Reflected signal energy

will occur at the first isolated attenuation cell 100 the signal encounters, due to the discontinuity of an open circuit in the isolated attenuation cell 100.

For example, if the digital switched attenuator 600 of FIG. 6 is controlled by the controller 612 to be in a state where the first two attenuation cells 100a, 100b are in attenuation mode, and the third attenuation cell 100c is in isolated mode, a signal that arrives at the input 602 is attenuated by the first two attenuation cells 100a, 100b, which may be, for example, an attenuation of 12 dB (e.g., having traveled through two 6 dB attenuation cells) before reaching the isolated third attenuation cell 100c. Any reflected signal, which is signal power being sent back toward the input 602, is further attenuated by another 12 dB as the reflected signal passes back through the first two attenuation cells 100a, 100b, resulting in the reflected signal being at least 24 dB lower than it might otherwise have been. In some embodiments, additional control lines may be included to control the input attenuation switch 110a and the shunt switch 112 separately from the output attenuation switch 110b, of one or more attenuation cells 100, to provide a signal path through a portion of the resistive network 106 of the attenuation cell 100 in isolated mode, further reducing the power of any portion of a reflected signal. In this manner, the digital switched attenuator 600 may be operated to substantially neither pass nor reflect signals received at either of the input 602 or the output 604, or both.

In at least one embodiment, attenuation cells 100 having higher attenuation levels may be provided at the periphery of the digital switched attenuator 600, e.g., the outermost attenuation cells may have higher attenuation levels than the innermost attenuation cells, along the series-connected plurality of attenuation cells. This will result in higher attenuation levels applied to a signal received from either the input 602 or the output 604 when the digital switched attenuator 600 is in an isolated state where periphery attenuation cells are in an attenuation mode and at least one central attenuation cell is in an isolated mode. As discussed above, this reduces the energy of any reflected signal or substantially absorbs all signal energy received.

Conventional multi-cell attenuators require DC-blocking capacitive components to ensure that adjacent switches may have opposing polarity as required by some usage states, and thus DC-blocking capacitors in these conventional designs provide DC isolation. The presence of DC-blocking elements between one or more attenuation cells allows for transistor channels in adjacent attenuation cells to be biased relative to each other, i.e., have a DC voltage offset

from the transistor channels of the adjacent attenuation cell. Aspects and embodiments of switched attenuators disclosed herein, however, alleviate or reduce the need for DC-blocking capacitors in part because impedance of the DC-blocking capacitors increases for lower frequency signals, requiring the capacitors to be made very large or else they will block the low frequency signal. Fabricating large capacitors is disadvantageous for the typical high cost of circuit space and desired small size and high efficiency of integrated circuits. Accordingly, aspects and embodiments disclosed herein allow multi-cell attenuator designs without capacitive coupling between the attenuation cells and therefore have no channel bias, do not require a negative voltage generator (NVG), have no standby current, and have increased suitability for lower frequency signals, such as into the single digit megahertz frequencies, e.g., 5 MHz. Accordingly, aspects and embodiments of switched attenuators as disclosed herein are particularly suitable for lower frequency applications, such as those supported by the Data over Cable Service Interface Specification (DOCSIS) 3.1 with an upstream carrier frequency band of 5 MHz to 204 MHz. Accordingly, aspects and embodiments of switched attenuators as disclosed herein are suitable for such applications and may be beneficially incorporated with amplifiers or within devices, such as described below with reference to FIGS. 9A, 9B, and 10, to provide tunable signal levels within cable modem applications. For example, switched attenuators as disclosed herein may be advantageously implemented to provide monotonic signal adjustments of 1dB step sizes or less with accuracy in the +/- 0.5dB or better across the DOCSIS 3.1 upstream frequency band.

Thus, aspects and examples provide various circuit designs to extend the bandwidth of a switched attenuator by, for example, directly DC coupling the attenuation cells in series with one another and without a capacitive component interposed between adjacent attenuation cells. For example, the output of a first attenuation cell may be directly coupled, without a capacitor, to the input of the next attenuation cell. Accordingly, a series of such attenuation cells may be DC coupled such that a DC component at the input may be conveyed from one attenuation cell to the next, and may be conveyed to the output. In some examples, a DC component may be blocked near the output to protect other equipment, or may be blocked after (or outside of) the switched attenuator, or may not be blocked at all.

In addition, example switched attenuators have been provided that incorporate resistor networks within the attenuation cells that are less susceptible to manufacturing variations.

It is to be appreciated that the attenuation cell 100 as shown in either of FIGS. 1 and 5 and the digital switched attenuator 600 as shown in FIG. 6 may be symmetrical with respect to input and output. The signal path through each attenuation cell 100, and thereby through the digital switched attenuator 600, is symmetrical with respect to inputs 102, 602 and outputs 104, 604. This results in attenuation cells 100 and a digital switched attenuator 600 capable of acting equally upon a signal whether the signal is received at the input or the output. Accordingly, the labels of input and output may be considered arbitrary and interchangeable in various embodiments, and the attenuation cell 100 or the digital switched attenuator 600 may be used in either forward or reverse directions.

According to other aspects, any of the attenuators disclosed herein may be incorporated into various packages, modules, or devices to create a commercial production unit. FIGS. 7-9 illustrate examples of modules that can include any of the configurable attenuators discussed herein. These example modules can include any combination of features associated with the attenuators disclosed herein, including isolation, step values, and compensation for manufacturing variations.

FIG. 7 is a block diagram of one example of a packaged module 700 that includes an embodiment of the attenuators disclosed herein as digital switched attenuator 710. The packaged module 700 includes a substrate 708, such as, for example, a package substrate for packaging of the circuitry of the digital switched attenuator 710 and other circuitry die. The packaged module 700 may also include a control element 712, such as a controller. Either of the digital switched attenuator 710 or the controller 712 may be implemented on a die or in the substrate 708. In some embodiments, the module 700 can include one or more packaging structures to, for example, provide protection and facilitate easier handling of the module 700. Such a packaging structure can include an overmold formed over a packaging substrate and dimensioned to substantially encapsulate the various dies and components thereon. The packaged module 700 further includes connectivity from the digital switched attenuator 710 and the controller 712 to the exterior of the substrate 708 to provide signal and control interconnections, such as input 702, output 704, and control interface 706. The connections 702, 704, and 706 may include contacts, wirebonds, solder bumps, balls, lands, pins, sockets, etc. The control interface 706 provides an interface to communicate to or control the configurable nature of the digital switched attenuator 710, for example, isolation settings,

attenuation step values, and compensation, as discussed herein. Any of the aspects and embodiments of the attenuators discussed herein may allow for bi-directional operation, such that, for example, the input 702 and the output 704 might be interchangeable in any given module 700.

5 FIG. 8A is a block diagram of an example of a coupler module 800a that includes an attenuator 810 configured to attenuate a signal from a coupler 806. Similar to module 700 above, the module 800a may include packaging and connectivity to external devices. In the example module 800a of FIG. 8A, shown are connections for the input 802, output 804, coupled output 808, and a control interface 812 to a control element 820. The coupler 806 may
10 provide a coupled portion of an input signal received at the input 802 and provide it to the attenuator 810, which attenuates the coupled signal in accordance with its current configuration. Module 800a allows a configurable coupling factor, at least because the attenuator 810 allows for various attenuation values of the coupled output signal.

 FIG. 8B is a block diagram of another example of a coupler module 800b that includes
15 an attenuator 810 configured to attenuate a coupled signal. In this example, the coupler 806 is configured for reverse operation, providing a coupled portion of an input signal received at the input 804 to the attenuator 810, which attenuates the coupled signal in accordance with its current configuration.

 FIG. 8C is a block diagram of another example of a coupler module 800c. In this
20 example, the coupler 806 is configured to allow bi-directional switched coupling. When in the configuration shown, the module 800c provides a forward coupled signal (coupled from a forward signal received at the input 802) to an attenuator 810a, by switching a forward coupled port to the attenuator 810a at switch 816a and by switching an isolation port to a termination impedance 814b at switch 816b. A reverse coupled signal (from a reverse signal received at
25 the output 802) may be provided to another attenuator 810b by alternating the configuration of the switches 816a, 816b. As shown, the termination impedances 814a and 814b may be variable or adjustable impedances. The coupler module 800c, for example, has two attenuated coupled outputs 808a and 808b for forward and reverse coupled signals, respectively.

 FIG. 8D is a block diagram of another example of a coupler module 800d. In this
30 example, the coupler 806 is configured to allow bi-directional switched coupling similar to FIG. 8C with only a single attenuator 810 and a single termination impedance 814. The

coupler 806 of FIG. 8D is selectively switchable to couple a forward signal or a reverse signal, and the attenuator 810 attenuates whichever coupled signal is provided by the coupler 806. In particular, the coupler 806 may provide a coupled portion of a signal received at the input 802 or a signal received at the output 804.

5 FIG. 8E is a block diagram of another example of a coupler module 800e. In this example, the coupler module 800e includes two couplers, 806a and 806b, that may be designed to operate for different frequencies or frequency bands. The coupler module 800e is an example of a dual-band attenuated coupler module. Each of the couplers 806a, 806b has an input 802a, 802b, respectively, and an output 804a, 804b, respectively. As shown, the coupling
10 lines of the couplers 806a, 806b are connected in series and each provides a forward coupled signal to an attenuator 810. A signal provided at coupled output 808 is an attenuated combination of a coupled signal from the first coupler 806a in the first frequency band and a coupled signal from the second coupler 806b in the second frequency band.

 FIG. 8F is a block diagram of another example of a coupler module 800f. The coupler
15 module 800f may be an example of a tri-band attenuated coupler module. The coupler module 800f includes three couplers 806a, 806b, 806c, that may be designed to operate for different frequencies or frequency bands. The coupled output of each coupler 806a, 806b, 806c, is combined by a triplexer 818 that provides combined coupled signals to the attenuator 810.

 While FIGS. 8A through 8F illustrate various embodiments of a coupler module with an
20 attenuator 810, other embodiments may be arranged differently. For example, a coupler module may have any number of one or more couplers whose various ports may be provided in various ways, and whose coupled outputs may be combined in various ways (e.g., by series connection, by a combiner, etc.), and whose connectivity to termination impedances, combiners, and/or attenuators may be selectively switched. Accordingly, any number of
25 couplers, attenuators, switches, combiners, and impedances may be arranged in various fashions to accommodate various application needs and/or operational characteristics. Additionally, a control circuit may control the various switches, adjustable impedances, and attenuation settings. Any of the modules may include packaging structures to provide protection and facilitate handling of the modules.

30 FIG. 9A is a block diagram of an example of an amplifier module 900a that includes two attenuators 910 configured to attenuate signals associated with a power amplifier 906.

Similar to module 700 and the modules 800a-f above, the module 900a may include packaging and connectivity to the exterior. In the example module 900a of FIG. 9A, shown are connections for the input 902 and output 904. A control interface 908 to a control element 920 of the attenuators 910 is also shown. The attenuators 910 may attenuate an input signal before the signal is amplified by the power amplifier 906, or may attenuate an amplified signal provided by the power amplifier 906, or both. The module 900a may have an alternate arrangement having only one of the attenuators 910. As shown, two (or more) attenuators 910 could be provided and connected such that attenuation occurs on both the input and the output of the power amplifier 906, which may yield flexibility in balancing or achieving total gain, noise figures, and other operational parameters. Accordingly, the amplifier module 900a may act as a variable gain amplifier because the ratio of the output signal to the input signal may be adjusted by the configurable attenuators 910.

FIG. 9B is a block diagram of another example of an amplifier module 900b. The amplifier module 900b includes two amplifiers 906 coupled in series on either side of a single attenuator 910. The amplifiers 906 may be adjustable gain amplifiers. The amplifier module 900b may include packaging as discussed above. The arrangement of amplifiers 906 and the attenuator 910 is one example of an arrangement that may allow flexibility in balancing or achieving total gain, noise figures, and other operational parameters in a variable gain amplifier. Alternate amplifier modules may include both multiple amplifiers and multiple attenuators for increased flexibility, and may include switching components to flexibly route signals.

FIG. 9C is a block diagram of an example of an intermediate frequency (IF) amplifier module 900c that includes an attenuator 910. The IF amplifier module 900c is shown in an example use with an antenna 912 that may receive a radio frequency (RF) signal and provide it to the input 902, from which a low-noise amplifier 914 boosts the signal strength. The amplified RF signal is mixed by a mixer 916 with an IF waveform from a local oscillator 918 and provided to an IF amplifier 906. In the example module 900c, the IF amplifier 906 has at least one integrated attenuator 910, similar to the amplifier module of FIG. 9A, to allow variable gain adjustment. The amplified IF signal may be provided to a demodulator 922 coupled to the output 904 of the IF amplifier module 900c. Similar to the example modules previously described, the IF amplifier module 900c may have a control interface 908. Alternate

embodiments may include one or more attenuators 910 coupled to the input or output of amplifier 906 rather than integrated with the amplifier 906.

While FIGS. 9A through 9C illustrate various embodiments of an amplifier module with an attenuator 910, other embodiments may be arranged differently.

5 FIGS. 7-9 described above illustrate various example modules that include switched attenuators as disclosed herein. Other modules in accord with those disclosed herein may include other components and features, such as, for example, a sensor, an antenna switch module, a transmitter, receiver, or transceiver, and any combination of the disclosed or other components. An attenuator of the types disclosed herein may be incorporated into any number
10 of packages, modules, or devices to accommodate changing operational parameters or specific applications.

 In an embodiment, a switched attenuator of the types disclosed herein may be incorporated into an electronic device. An example of such a device is shown in FIG. 10, which is a block diagram of a communication device 1000 that can have one or more switched
15 attenuators in accordance with any of the principles and advantages discussed herein. The example communication device 1000 may be a wireless device, such as, for example, a mobile phone, a smart phone, a tablet, a wireless access point, a router, a modem, an end point, or the like, or may be a wired device, such as, for example, a cable modem, a set top box, or the like, or may be a combination of a wired and wireless device. A communication device may include
20 additional elements not shown in FIG. 10 and/or may include a sub-combination of those elements shown.

 The example communication device 1000 may include an external interface 1030a, 1030b, to which a communication cable 1036 or an antenna 1034, for example, may be connected for transmitting and receiving communication signals, such as radio frequency (RF)
25 signals. The communication device 1000 may also or alternatively have an internal antenna 1032. A coupler 1060 may provide to a sensor 1062 a coupled signal of the RF signal going to or from the interface 1030 and/or the internal antenna 1032, for monitoring and adjusting power levels and/or transmission mismatch characteristics. A switch module 1050 may control or direct received RF signals from the interface 1030 to a transceiver 1020, and control or
30 direct RF signals from a power amplifier 1040 to the interface 1030. The transceiver 1020 may be controlled by a baseband sub-system 1070 having a user interface 1072 and a memory 1074,

and the example communication device 1000 may have a power management system 1080 and a power source 1082, such as a battery or power supply.

One or more switched attenuators in accord with those disclosed herein may be incorporated in the communication device 1000 in a number of configurations in accord with
5 desired operational characteristics of the communication device 1000. For example, a switched attenuator 1010 may be included to attenuate an input signal to the power amplifier 1040. A switched attenuator 1012 may attenuate an output signal of the power amplifier 1040. An attenuator 1014 and/or a switched attenuator 1016 may attenuate a transmit or receive signal, or both, between the switch module 1050 and the interface 1030 and/or the internal antenna 1032,
10 with or without a coupler 1060 in between. Additionally, a coupled output from the coupler 1060 may be configured with a switched attenuator 1018. Any of the switched attenuators 1010, 1012, 1014, 1016, and 1018 may be present, or additional switched attenuators may be present, in various additional or alternate arrangements, to attenuate a signal at varying locations to accommodate changing operational parameters or applications.

15 Having described above several aspects of at least one example, it is to be appreciated various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure and are intended to be within the scope of the invention. Accordingly, the foregoing description and drawings are by way of example only, and the scope of the invention should be
20 determined from proper construction of the appended claims, and their equivalents.

What is claimed is:

CLAIMS

1. An attenuation cell for use in a digital switched attenuator, the attenuation cell comprising:
 - an attenuation path having an input, a first switch, a resistive network, a second switch, and an output, the resistive network electrically disposed between the first switch and the second switch and configured to provide a desired attenuation from the input to the output;
 - a bypass path in parallel with the attenuation path and having a bypass switch disposed between the input and the output; and
 - a shunt switch coupled between the resistive network and a reference node to selectively connect the resistive network to the reference node.
2. The attenuation cell of claim 1 wherein at least one of the first switch, the second switch, the bypass switch, and the shunt switch include a switching element that is one of a transistor, a diode, or a microelectromechanical element.
3. The attenuation cell of claim 2 wherein the bypass switch includes a plurality of switching elements equal in number to a combined number of switching elements in the first switch and the second switch.
4. The attenuation cell of claim 1 wherein the bypass switch, the first switch, and the second switch are each formed on a common integrated circuit die.
5. The attenuation cell of claim 4 wherein the bypass switch has substantially similar parasitic characteristics as the first switch and the second switch combined.
6. The attenuation cell of claim 4 wherein the bypass switch, the first switch, and the second switch each have a switching element of substantially similar parasitic characteristics.

7. The attenuation cell of claim 6 wherein the bypass switch, the first switch, and the second switch each include one or more switching elements and all of the switching elements are of a same type.
8. The attenuation cell of claim 1 wherein the shunt switch includes a plurality of switching elements.
9. The attenuation cell of claim 8 wherein the shunt switch includes at least four switching elements.
10. The attenuation cell of claim 9 wherein the shunt switch includes eight switching elements.
11. The attenuation cell of claim 10 wherein the shunt switch includes at least one field effect transistor or a bipolar junction transistor.
12. The attenuation cell of claim 1 wherein the resistive network is one of a Pi-network, a T-network, a delta network, or a bridged T-network.
13. The attenuation cell of claim 12 wherein the resistive network includes a plurality of identical resistive elements.
14. The attenuation cell of claim 12 wherein the resistive network has a characteristic impedance of 50 Ohms.
15. The attenuation cell of claim 12 wherein the resistive network includes a plurality of resistors, at least two of the plurality of resistors in parallel and at least two of the plurality of resistors in series.

16. The attenuation cell of claim 1 further comprising a control line configured to apply a control to at least one of the first switch, the second switch, the bypass switch, and the shunt switch.

17. A module comprising the attenuation cell of any one of claims 1-16.

18. The module of claim 17 further comprising at least one of an amplifier and a coupler coupled to the attenuation cell.

19. A communication device comprising a transceiver configured to produce a transmit signal and to receive a receive signal, an antenna coupled to the transceiver and configured to transmit the transmit signal and to receive the receive signal, and an attenuation cell of any one of claims 1-16 configured to attenuate at least one of the transmit signal, the receive signal, and a coupled signal derived from one of the transmit signal or the receive signal.

20. A switched attenuator comprising:

an input to receive an input signal;

an output to provide an attenuated signal;

a plurality of attenuation cells directly coupled in series and coupled to the input and the output; and

a controller coupled to one or more of the plurality of attenuation cells, the controller configured to control an operational state of the one or more of the plurality of attenuation cells.

21. The switched attenuator of claim 20 wherein the plurality of attenuation cells includes an input cell, an output cell, and at least one intermediate cell, the at least one intermediate cell being interposed between the input cell and the output cell with no capacitive element therebetween.

22. The switched attenuator of claim 21 wherein the operational state of the one or more of the plurality of attenuation cells includes at least one of an attenuation mode, a bypass mode, and an isolated mode.

23. The switched attenuator of claim 21 wherein the controller is configured to control the operational state of the one or more of the plurality of attenuation cells to place the switched attenuator into an open circuit mode in which the switched attenuator provides at the output substantially none of the input signal.

24. The switched attenuator of claim 21 wherein the controller is configured to control the operational state of the one or more of the plurality of attenuation cells to place the switched attenuator into an open circuit mode in which the switched attenuator absorbs a majority of the input signal.

25. The switched attenuator of either of claim 23 or claim 24 wherein the controller is configured to place the switched attenuator into the open circuit mode at least by controlling a first attenuation cell of the plurality of attenuation cells to attenuate a signal received at an input of the first attenuation cell, a level of attenuation being determined by a resistive network of the first attenuation cell, and by controlling a second attenuation cell of the plurality of attenuation cells to reject a signal received at an input of the second attenuation cell by controlling switching elements in the second attenuation cell to be in an open circuit condition.

26. The switched attenuator of claim 21 wherein the controller is configured to place the switched attenuator into an open circuit mode by controlling at least one of the plurality of attenuation cells to be in an attenuation mode and controlling at least one other of the plurality of attenuation cells to be in an isolated mode.

27. The switched attenuator of claim 21 wherein the controller is configured to control the operational state of the one or more of the plurality of attenuation cells to place the switched attenuator into an attenuation mode in which the switched attenuator provides one of a plurality

of attenuation levels, the plurality of attenuation levels indicative of a power level of the attenuated signal relative to a power level of the input signal.

28. A module comprising the switched attenuator of any one of claims 20-24 and claims 26-27.

29. The module of claim 28 further comprising a power amplifier connected to one of the input and the output.

30. The module of claim 28 further comprising a coupler connected to one of the input or the output.

31. A communication device comprising a transceiver configured to produce a transmit signal and to receive a receive signal, and the switched attenuator of any one of claims 20-24 and claims 26-27 configured to attenuate at least one of the transmit signal, the receive signal, and a coupled signal derived from one of the transmit signal or the receive signal.

32. The communication device of claim 31 further comprising an antenna coupled to the transceiver and configured to transmit the transmit signal and to receive the receive signal.

33. A switched attenuator comprising:
an input to receive an input signal;
an output to provide an attenuated signal; and
a plurality of attenuation cells directly coupled in series between the input and the output and having no capacitive coupling element interposed between adjacent attenuation cells of the plurality of attenuation cells, the plurality of attenuation cells including an input cell coupled to the input and an output cell coupled to the output, each respective attenuation cell of the plurality of attenuation cells including
an attenuation path having a first switch, a resistive network, and a second switch,

a bypass path in parallel with the attenuation path and having a bypass switch,
and
a shunt switch coupled between the resistive network and a reference node to selectively connect the resistive network to the reference node.

34. The switched attenuator of claim 33 wherein the bypass switch of each respective attenuation cell includes a plurality of switching elements equal in number to a combined number of switching elements in the first switch and the second switch of the respective attenuation cell.

35. The switched attenuator of claim 33 wherein the bypass switch of each respective attenuation cell has a substantially similar parasitic characteristic to a combined parasitic characteristic of the first switch and the second switch of the respective attenuation cell.

36. The switched attenuator of claim 33 wherein all the switching elements of the bypass switch, the first switch, and the second switch of the respective attenuation cell are of a same type.

37. The switched attenuator of claim 33 wherein each of the plurality of attenuation cells is identical except for the resistive network included in the respective attenuation cell.

38. The switched attenuator of claim 33 wherein each resistive network included in the respective attenuation cell includes a plurality of identical resistive elements.

39. The switched attenuator of claim 33 further comprising a controller coupled to one or more of the plurality of attenuation cells, the controller configured to control an operational state of the one or more of the plurality of attenuation cells.

40. A module comprising the switched attenuator of any one of claims 33-39.

41. The module of claim 40 further comprising a power amplifier connected to one of the input and the output.
42. The module of claim 40 further comprising a coupler connected to one of the input or the output.
43. A communication device comprising a transceiver configured to produce a transmit signal and to receive a receive signal, and the switched attenuator of any one of claims 33-39 configured to attenuate at least one of the transmit signal, the receive signal, and a coupled signal derived from one of the transmit signal or the receive signal.
44. The communication device of claim 43 further comprising an antenna coupled to the transceiver and configured to transmit the transmit signal and to receive the receive signal.

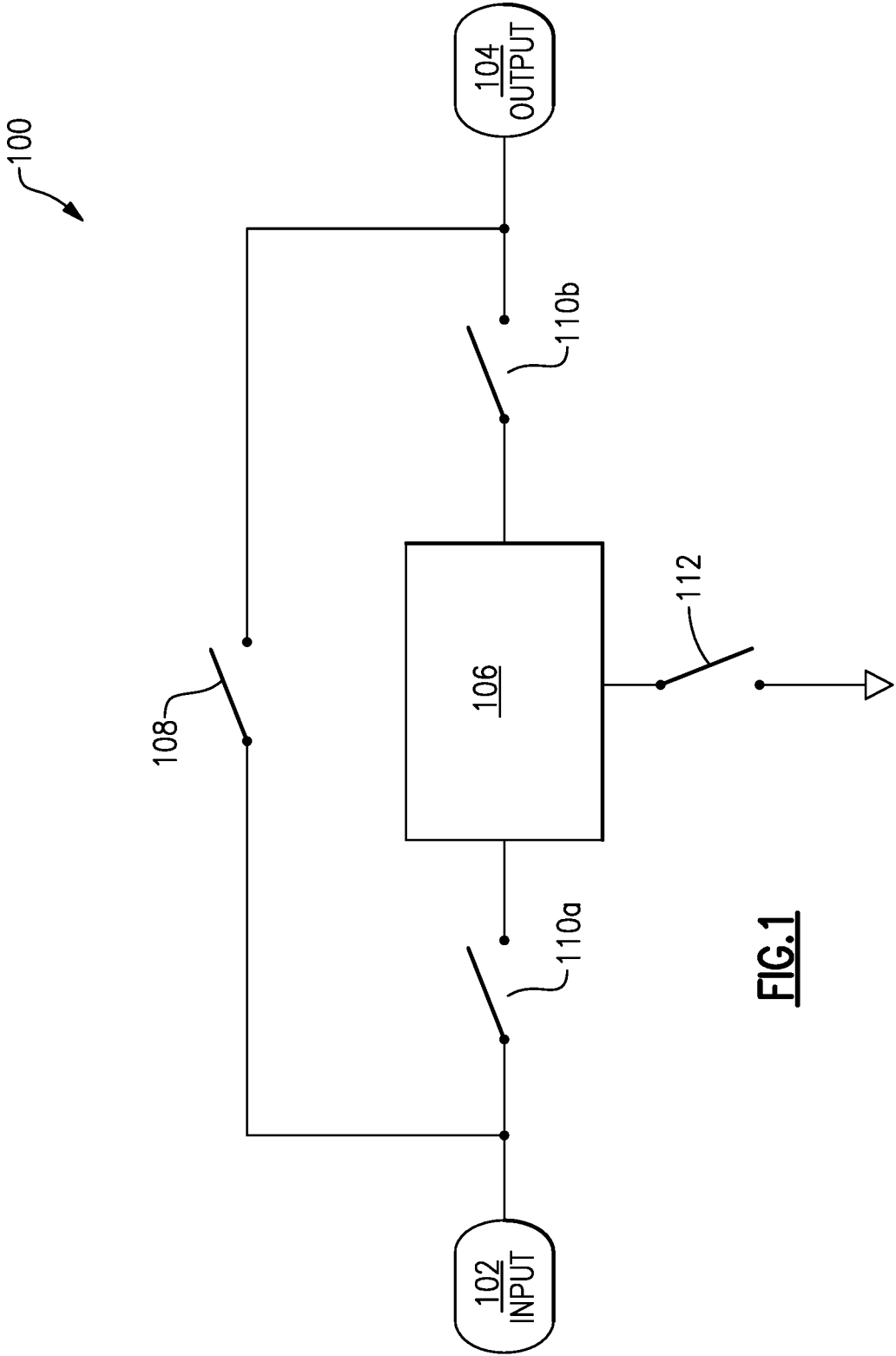


FIG.1

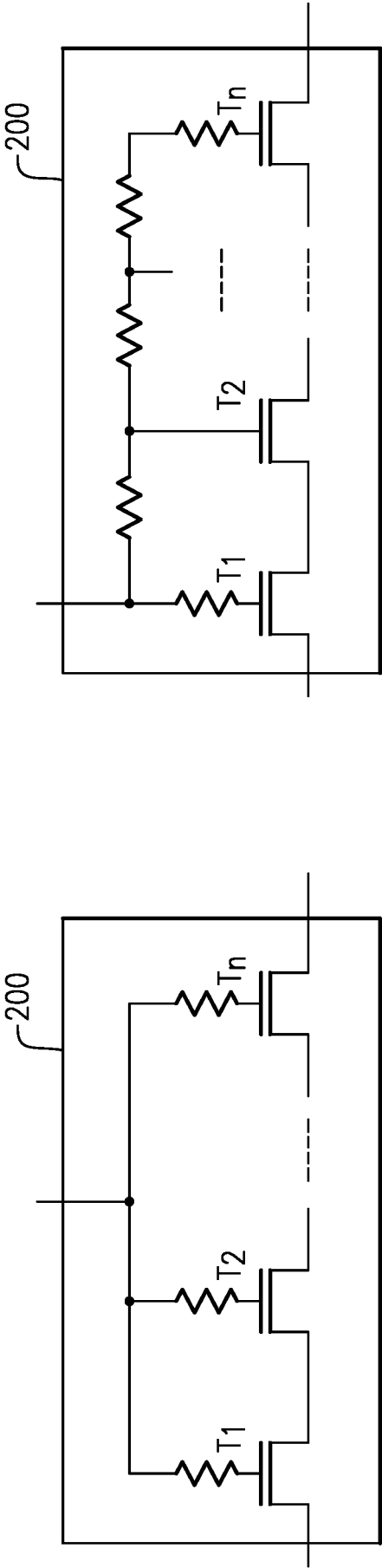


FIG. 2A

FIG. 2B

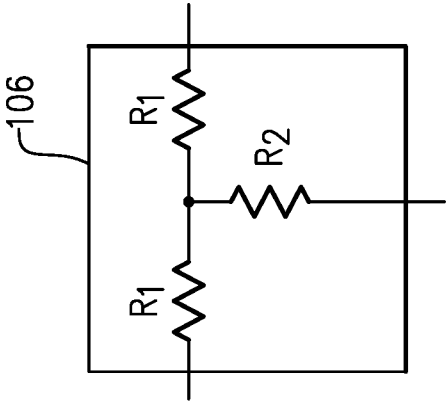


FIG. 3A

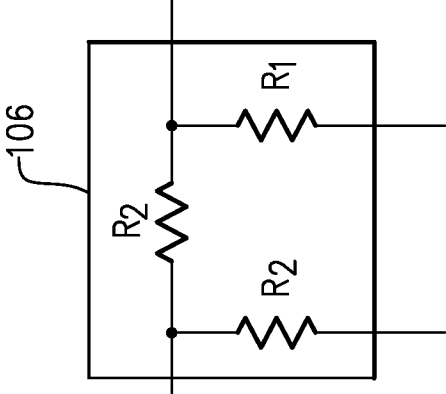


FIG. 3B

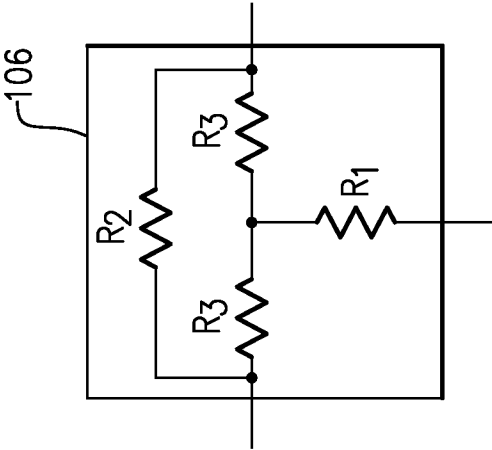


FIG. 3C

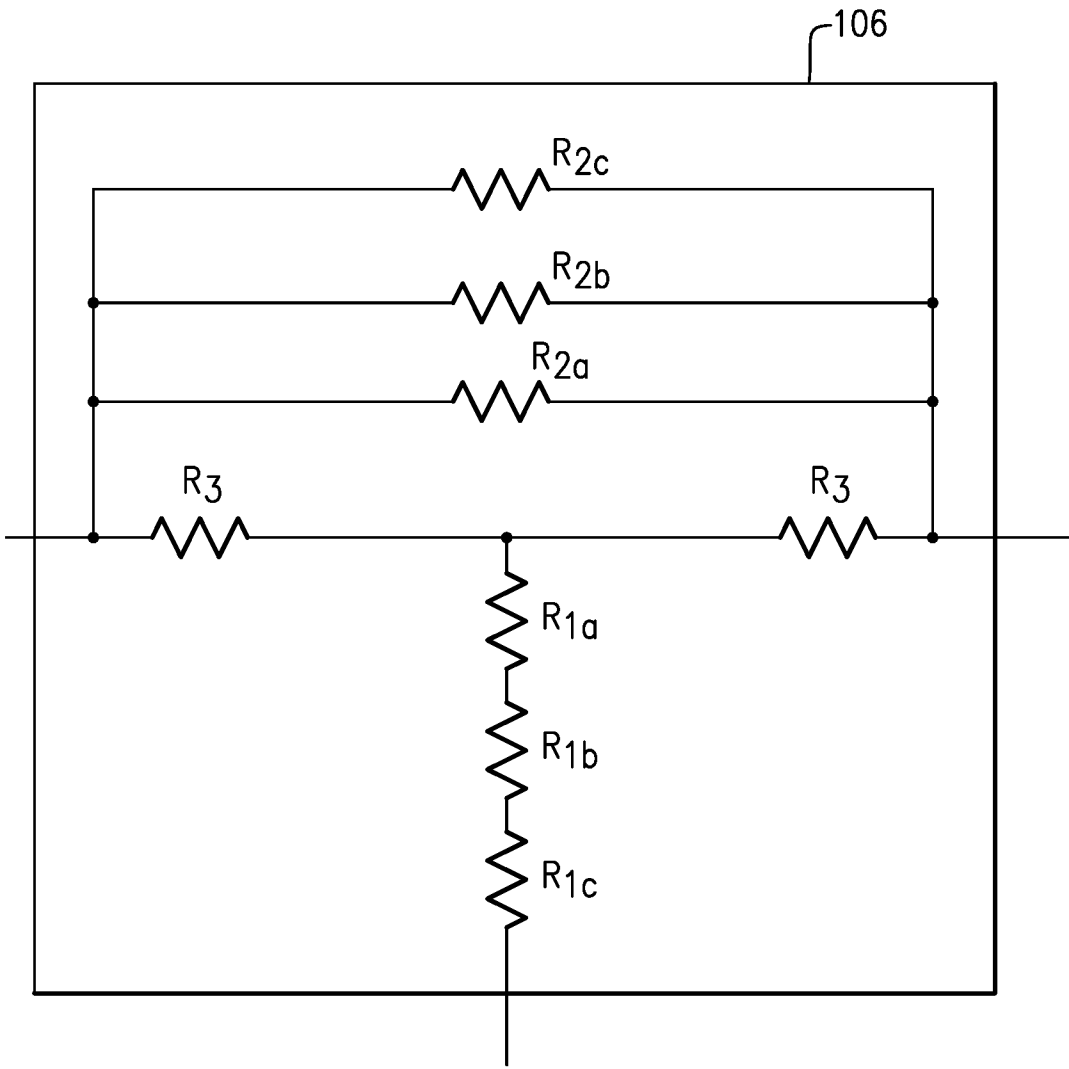
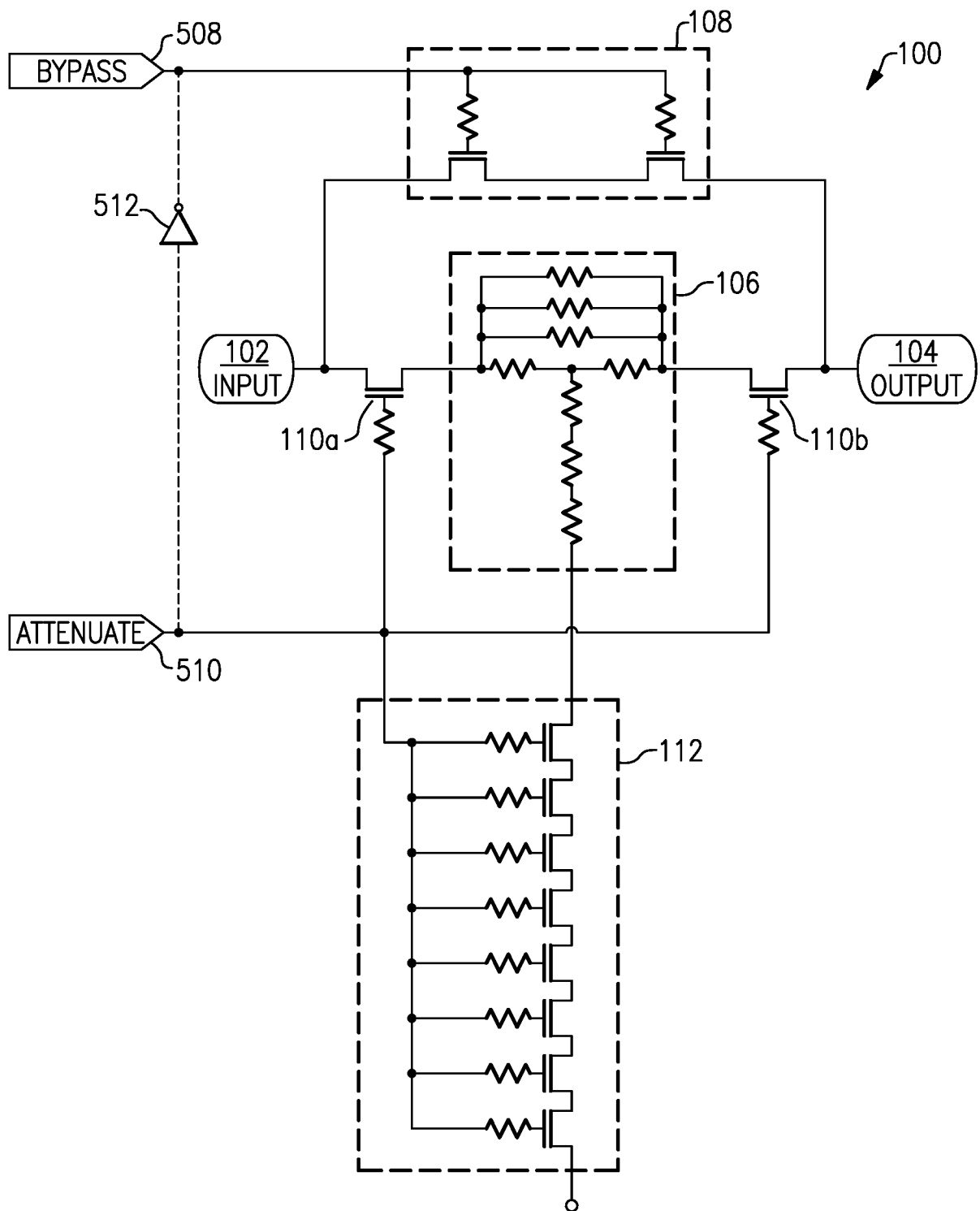


FIG.4

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**FIG.5**

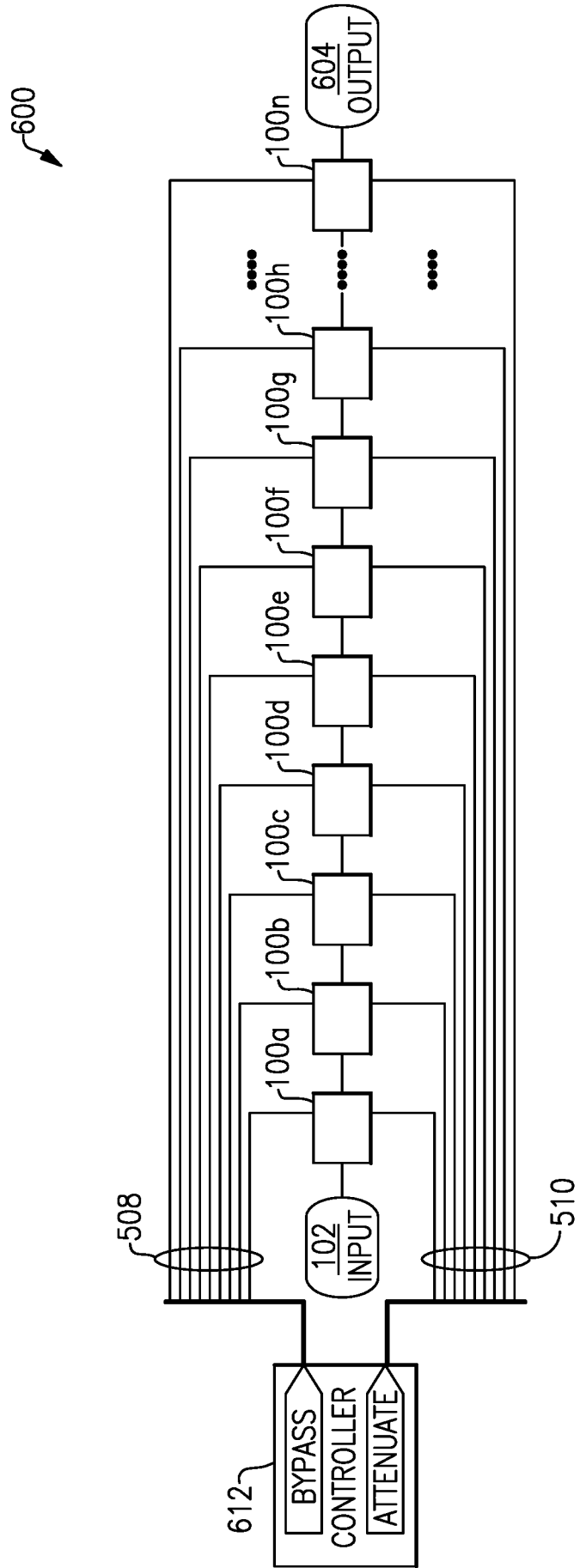
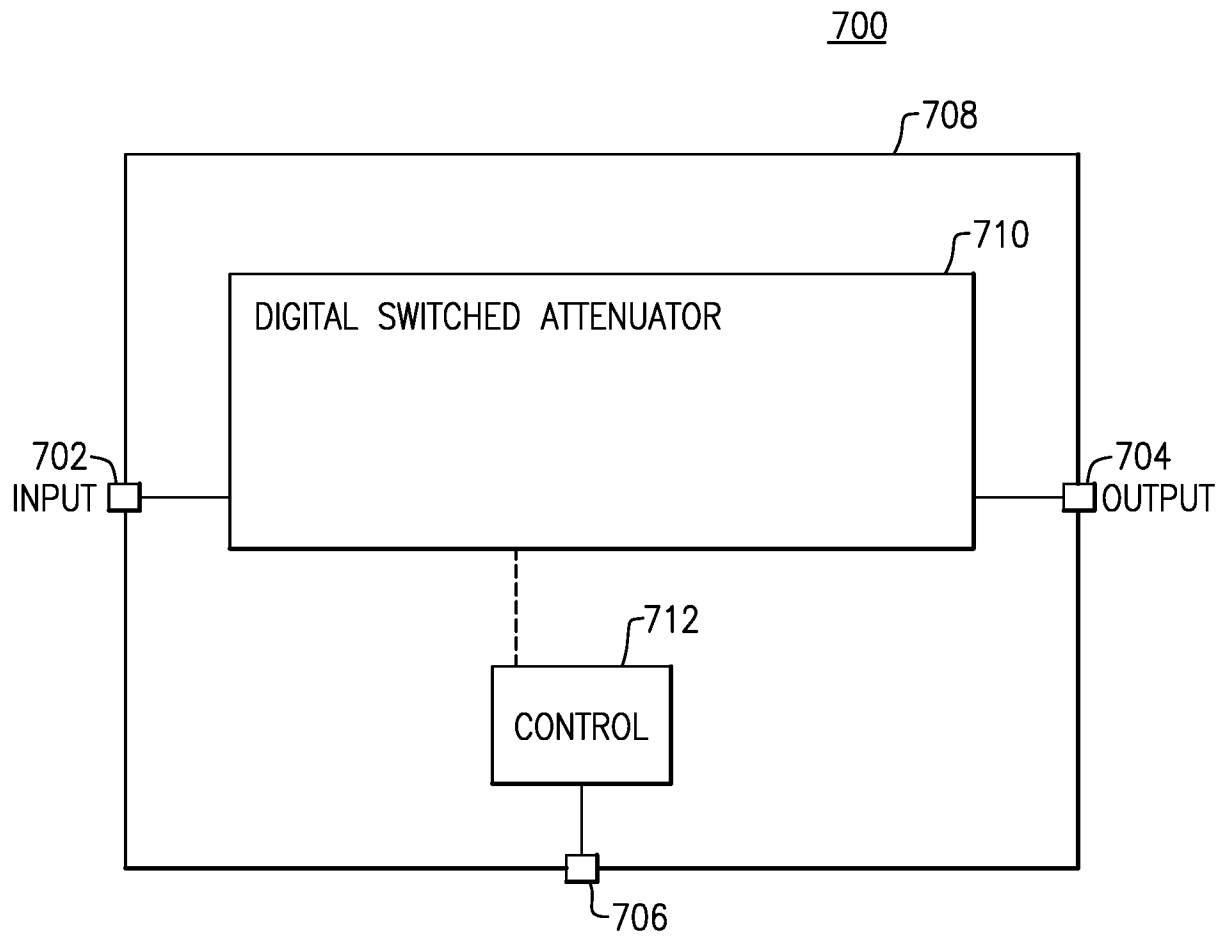
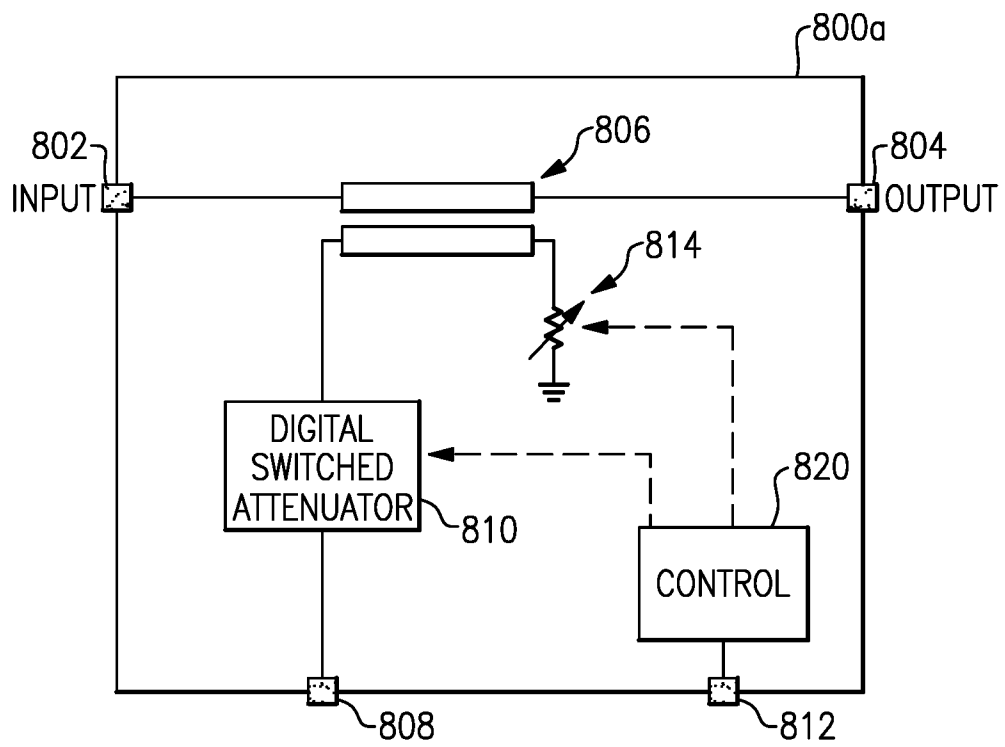


FIG.6

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**FIG.7**

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**FIG. 8A**

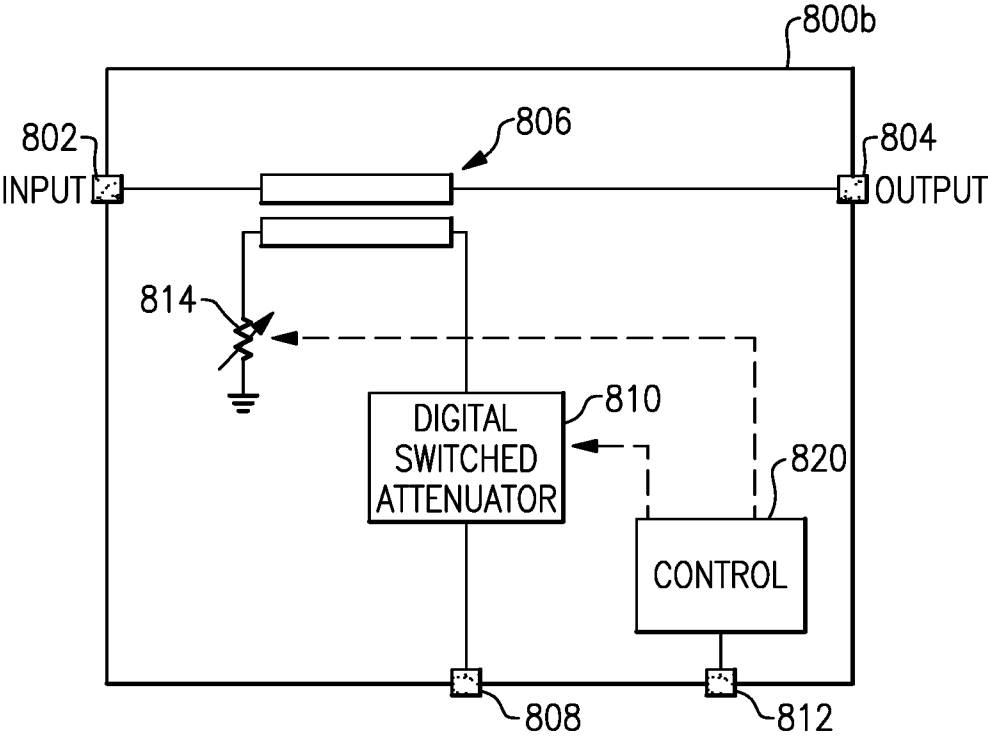
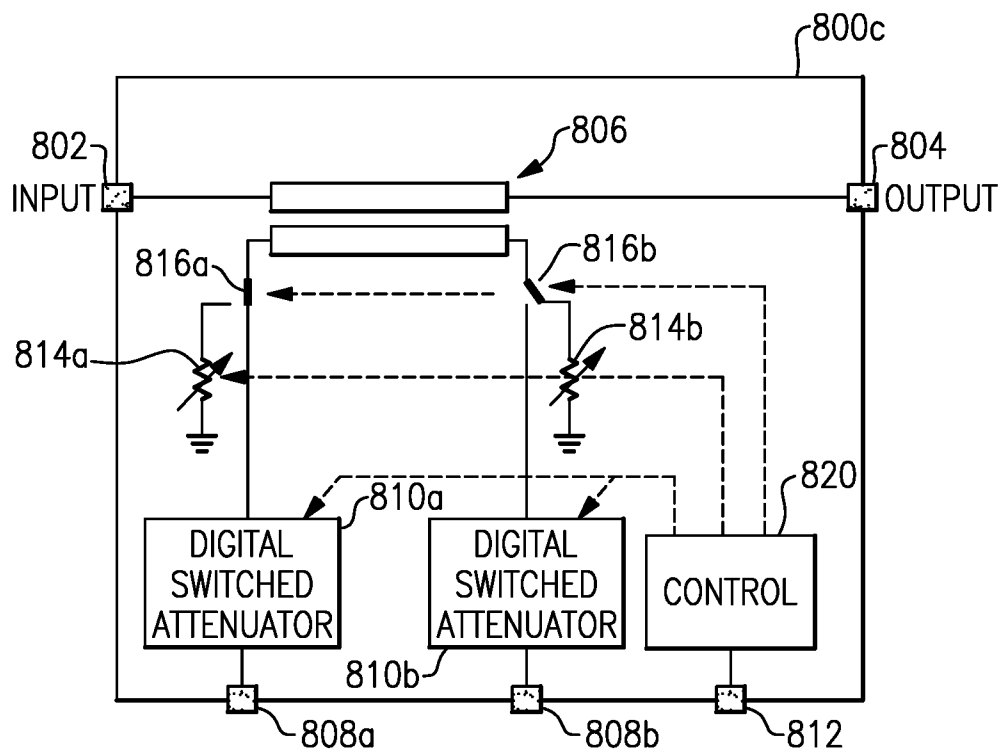
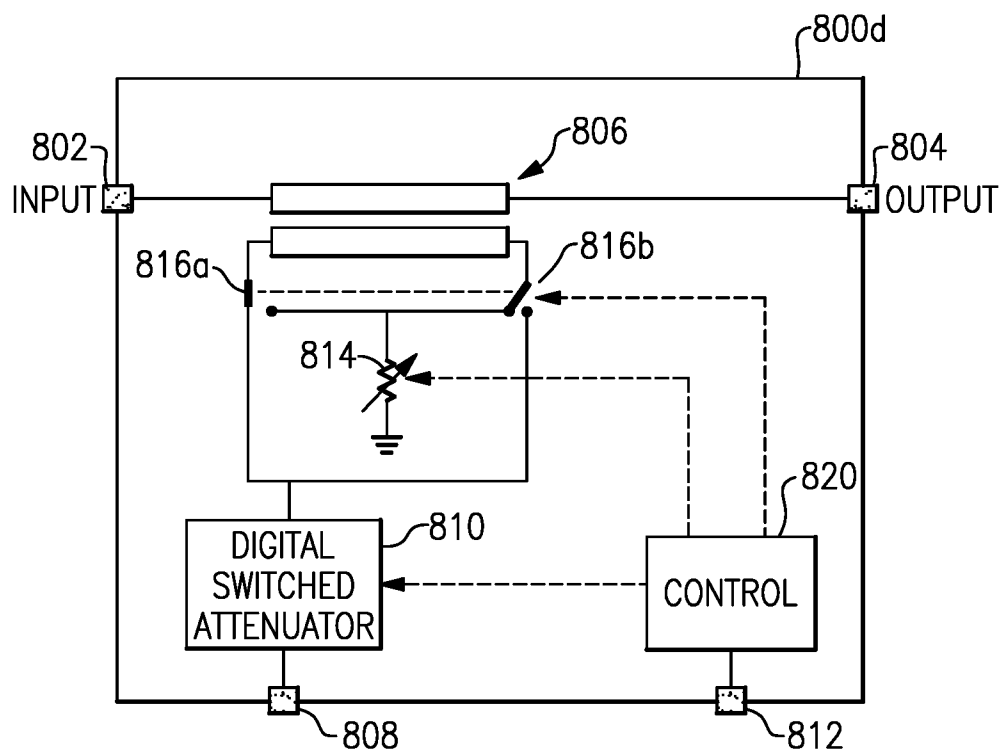


FIG.8B

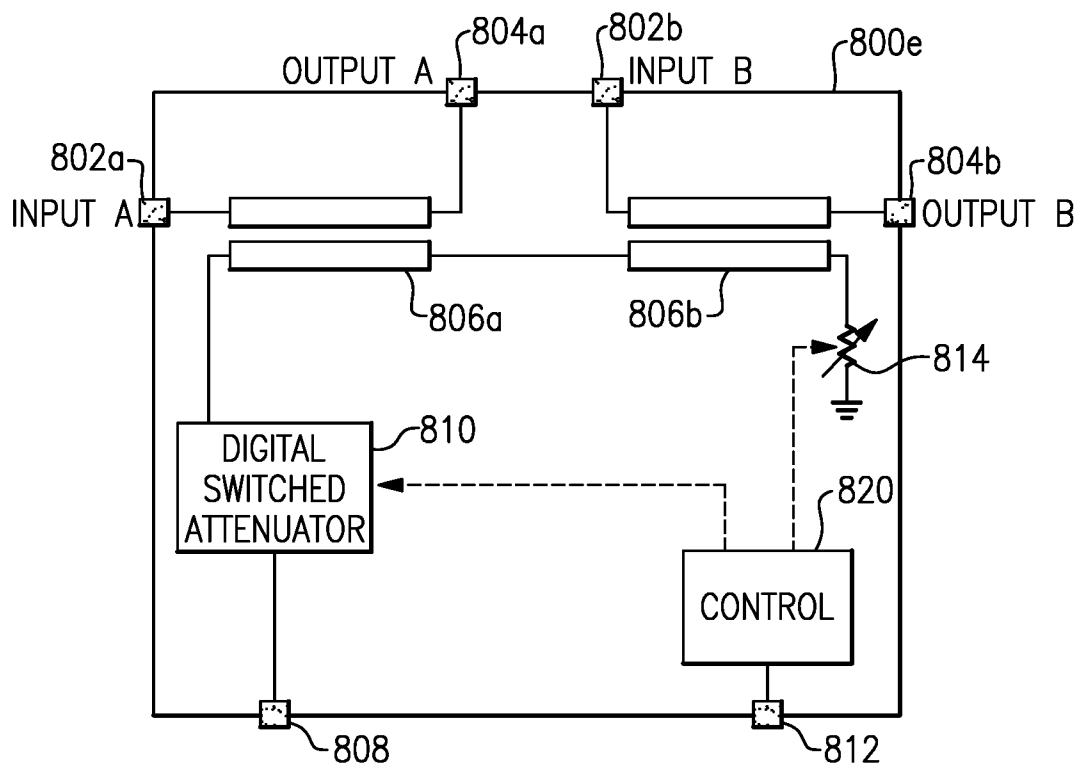
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**FIG.8C**

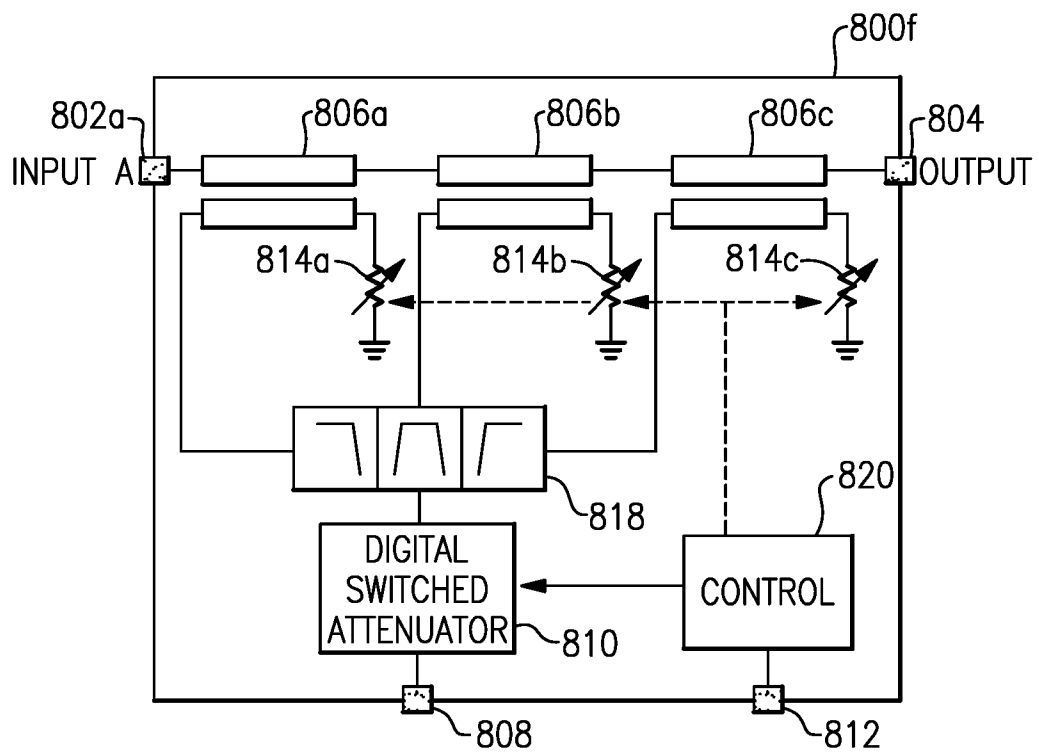
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**FIG.8D**

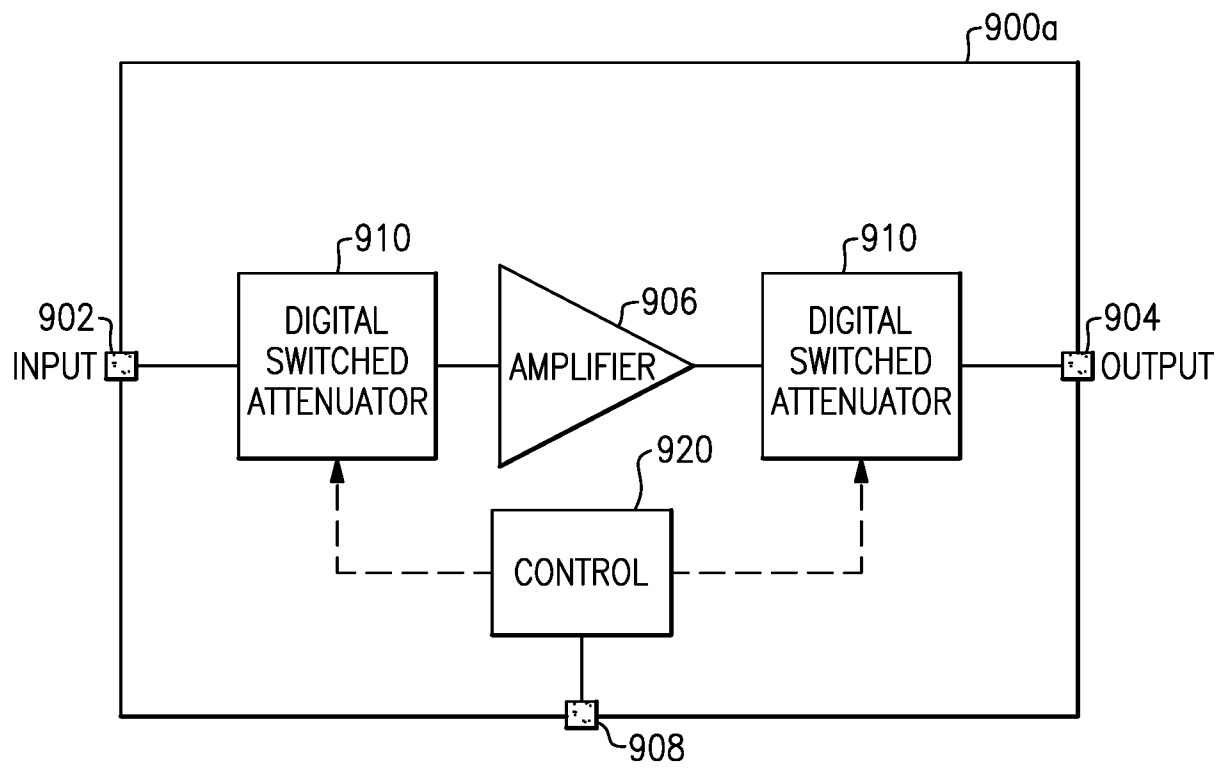
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**FIG. 8E**

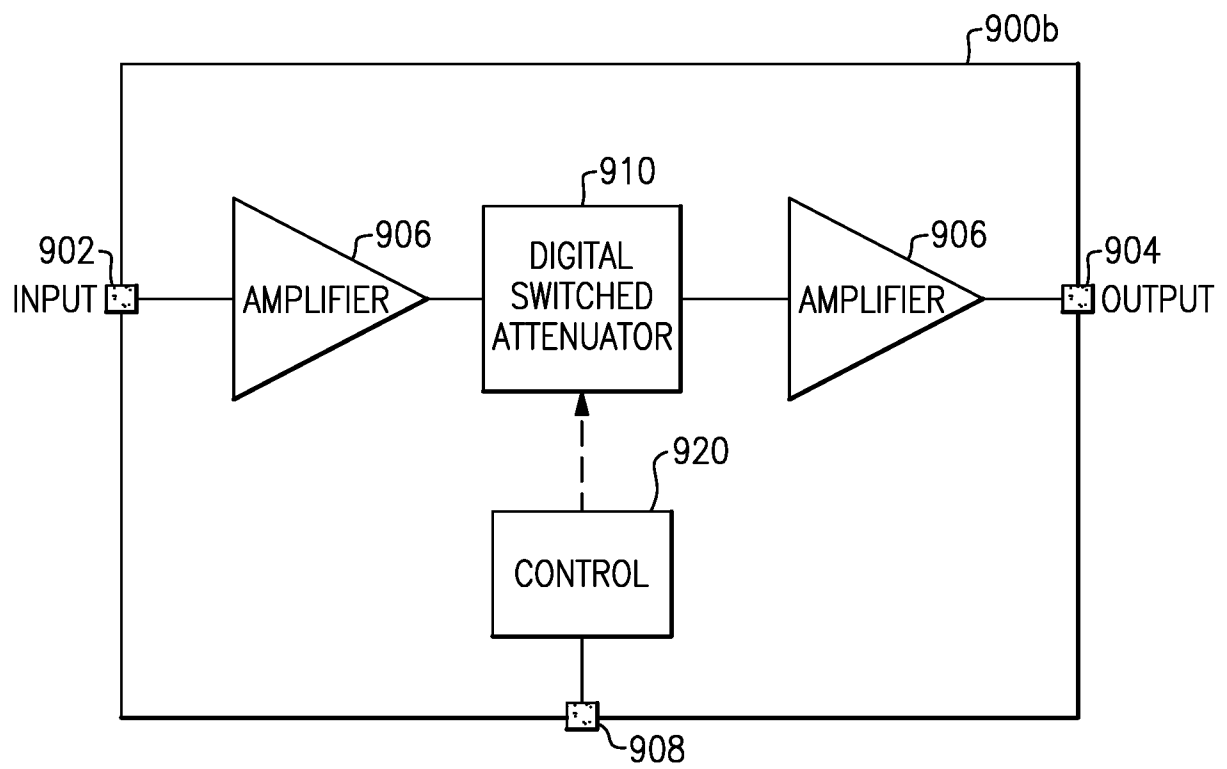
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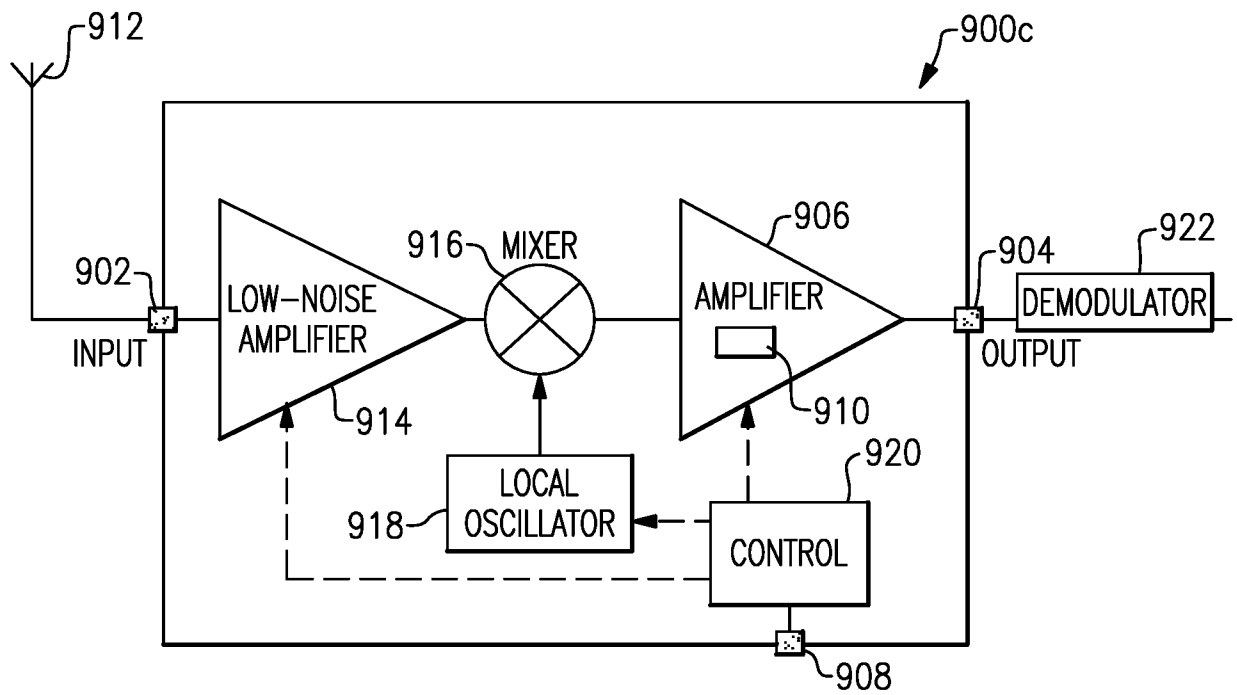
**FIG.8F**

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**FIG.9A**

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**FIG.9B**

**FIG.9C**

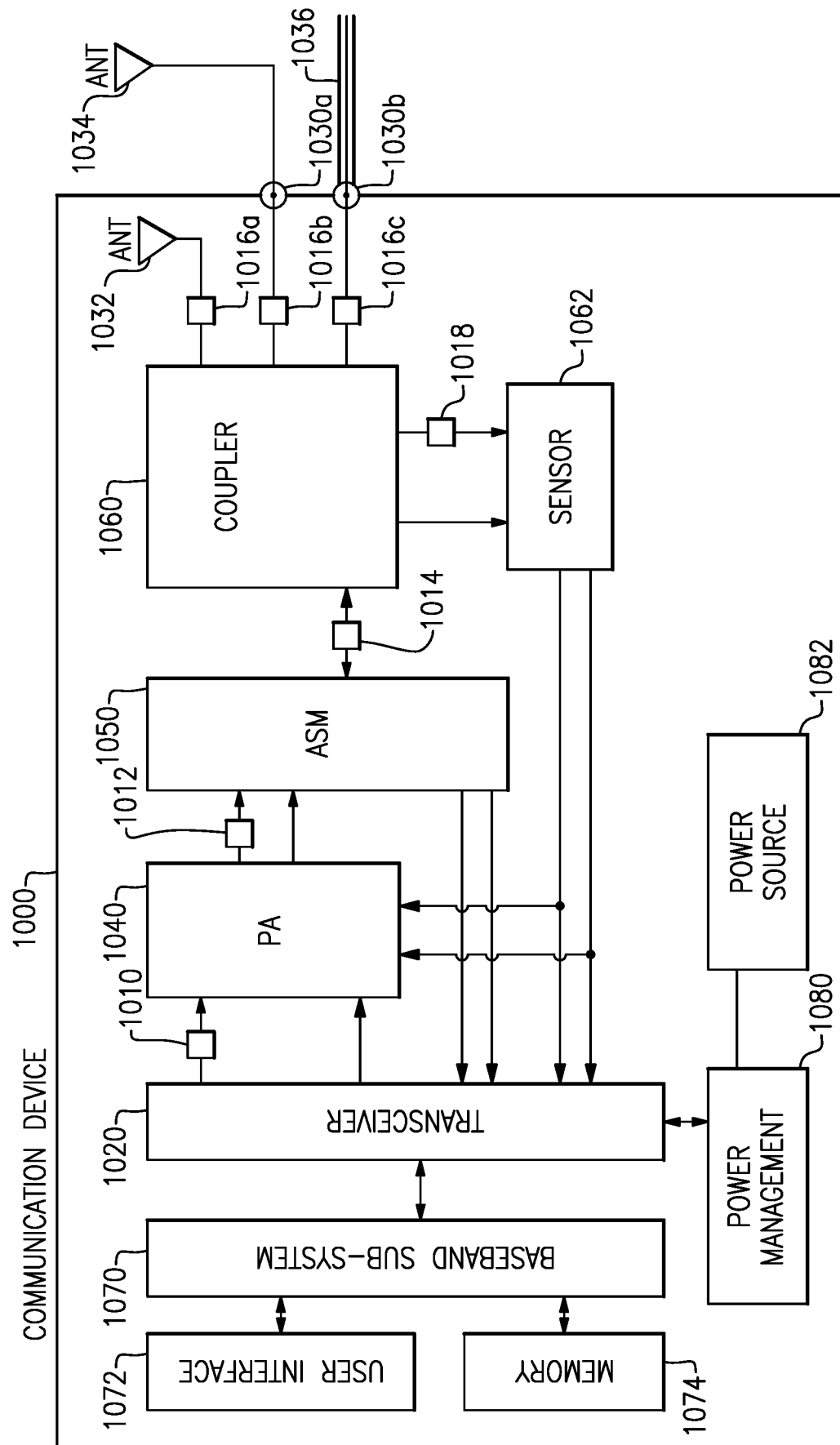


FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/047040**A. CLASSIFICATION OF SUBJECT MATTER****H01P 1/22(2006.01)i, H03H 11/24(2006.01)i**

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)

H01P 1/22; H03H 7/24; H01F 38/14; H03H 11/24

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: attenuation path, bypass switch, shunt switch, resistive network

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2015-0326204 A1 (SKYWORKS SOLUTIONS, INC.) 12 November 2015 See paragraphs [0035], [0050], [0068], [0071], [0086], [0089], [0101]-[0104], [0128]; claim 1; and figures 3-5, 8A-8B.	20-26, 28-29, 31-32
Y		1-19, 27, 30, 33-44
Y	US 2006-0244548 A1 (PETER NOEST et al.) 02 November 2006 See paragraph [0013]; claim 1; and figure 1.	1-19, 33-44
Y	US 2016-0118959 A1 (ANALOG DEVICES GLOBAL) 28 April 2016 See paragraphs [0041]-[0059]; claim 1; and figures 2-6.	27
Y	US 2008-0100404 A1 (MICHAEL VICE) 01 May 2008 See paragraphs [0018]-[0029]; claim 7; and figure 2.	30, 42
A	US 2015-0171828 A1 (PEREGRINE SEMICONDUCTOR CORPORATION) 18 June 2015 See paragraphs [0005]-[0011], [0026]-[0027]; and figures 1-5.	1-44
A	US 2016-0134259 A1 (PEREGRINE SEMICONDUCTOR CORPORATION) 12 May 2016 See paragraphs [0004]-[0009], [0035]-[0043]; and figures 1-5.	1-44



Further documents are listed in the continuation of Box C.



See patent family annex.

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"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

27 November 2017 (27.11.2017)

Date of mailing of the international search report

27 November 2017 (27.11.2017)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2017/047040

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