



(51) International Patent Classification:

H01P 5/16 (2006.01) H03H 7/48 (2006.01)

(21) International Application Number:

PCT/EP2019/073980

(22) International Filing Date:

09 September 2019 (09.09.2019)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

1814756.1 11 September 2018 (11.09.2018) GB

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,

DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: IMPROVEMENTS IN AND RELATING TO POWER DIVIDER / COMBINER CIRCUITS

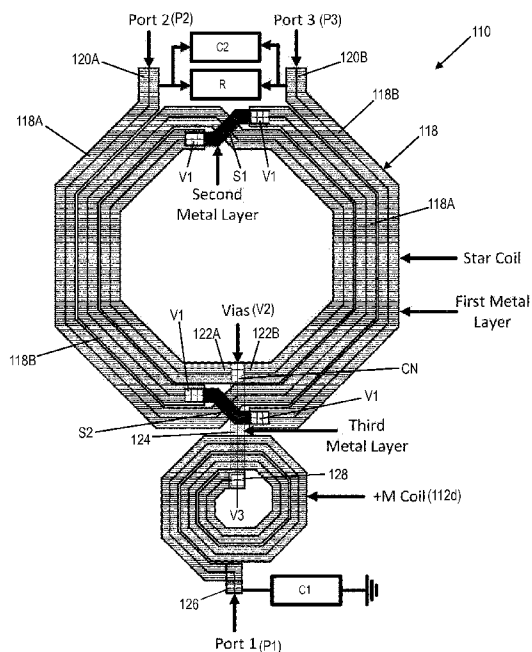


Fig. 6

(57) Abstract: A Wilkinson power divider/power combiner device has a lumped-element circuit topology that includes a respective inductor representing first and second transmission lines. The inductors are implemented, respectively, by first and second mutually coupled conductive windings of a coupled coil. The device is relatively small when compared to conventional alternatives, and is well suited to implementation in an integrated circuit (IC).

Improvements in and relating to Power Divider / Combiner Circuits**Field of the Invention**

- 5 The present invention relates to power divider / combiner circuits. The invention relates particularly to power divider / combiner circuits of a type commonly known as a Wilkinson power divider, or Wilkinson power combiner.

Background to the Invention

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Power dividers are electrical devices that couple a defined amount of the electromagnetic power in a transmission line to a port enabling a signal to be used in another circuit. Power dividers are used commonly in the field of radio technology, for example in microwave engineering. Passive power dividers are reciprocal devices and therefore can also be used as power combiners. A Wilkinson

15 power divider (or power combiner) is a type of power divider/combiner circuit that can achieve isolation between output ports (in the case of a power divider) or input ports (in the case of a power combiner) while maintaining a matched condition on all ports.

20

An ideal Wilkinson circuit is lossless and has excellent impedance matching at all ports (i.e. low return loss) as well as high isolation between the two circuit branches. Due to these outstanding characteristics coupled with the simplicity of its structure, Wilkinson power divider / combiner circuits are extensively used in various radio frequency (RF) front-end transceiver circuits (e.g. power amplifiers, voltage-controlled oscillators, etc.), phased array radars, and other applications, particularly in the field of RF (including microwave) engineering.

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Known power divider / combiner circuits, particularly Wilkinson type circuits, are considered to be relatively large and to be relatively time-consuming to design. It would be desirable to mitigate these problems.

30 Summary of the Invention

The invention provides a power combiner or power divider device comprising:

- a first port;
- a second port;
- 35 a third port, and

- a common circuit node between said first, second and third ports,

wherein said second port is connected to said common circuit node by second port circuit branch comprising at least one inductive element, and said third port is connected to said common circuit node by a third port circuit branch comprising at least one inductive element,

and wherein at least one inductive element of said second port circuit branch and at least one inductive element of said third port circuit branch are implemented, respectively, by first and second mutually coupled conductive windings of a coupled coil.

- 5 In preferred embodiments, the device is of a type commonly known as a Wilkinson power divider or Wilkinson power combiner. The device preferably has a lumped-element circuit topology including a respective inductor (or optionally more than one respective inductor) representing a respective transmission line of the power divider/combiner. In particular, said at least one inductive element of said second port circuit branch, and said at least one inductive element of said third port circuit
- 10 branch may each be a lumped-element representation of a respective transmission line of a Wilkinson power divider or power combiner. In preferred embodiments, therefore, the first and second windings of the coupled coil implement, respectively, an inductor (or inductors as applicable) that represents a respective transmission line.
- 15 Typically, each of said first and second windings has a respective first end and a respective second end, each winding being shaped to define at least part of one turn, typically one or more turns, between its first and second ends. Optionally, each of said first and second windings is planar. Said first and second windings may be co-planar with one another.
- 20 Preferably, said first and second windings are interspersed with one another such that one or more turns, or part of a turn, of each winding is located between one or more turns, or part of a turn, of the other winding.

In typical embodiments, a capacitor is connected between said second port and said third port. Said

25 capacitor is conveniently connected between the first and second windings, preferably between a respective first ends of each winding.

In some embodiments, said first port is connected to said common circuit node by a first port circuit branch comprising at least one inductive element. Said first port circuit branch typically includes a

30 shunt capacitor connected between said first port and RF ground. In some embodiments, said coupled coil implements an inverting star network of inductive elements connected between said second and third ports and said common circuit node. Said inverting star network may comprise a first inductive element connected between said common circuit node and an internal node of the star network, a second inductive element connected between said second port and said internal node,

35 and a third inductive element connected between said third port and said internal node. Preferably, said first inductive element has an inductance of $-M$, and said second and third inductive elements each has an inductance of $L+M$, where L and M are the self inductance and mutual inductance, respectively, of the coupled coil. Advantageously, said first and second windings of the coupled coil implement a respective one of said second and third inductive elements.

Typically, said first port circuit branch comprises an inductor between said first port and said common circuit node. Said inductor may be connected in series between said first port and said common circuit node. Preferably, said inductor has an inductance that is equal to, or substantially equal to, the mutual inductance M between said first and second windings. Said inductor is optionally
 5 included in a resonator circuit that is connected between said first port and said common circuit node. Said resonator circuit may comprise said inductor in parallel with a capacitor. Advantageously, said resonator circuit is configured to serve as a harmonic trap filter, optionally a second harmonic trap filter. Said inductor may have an inductance that is equal to, or substantially equal to, three quarters of the mutual inductance M between said first and second windings. Preferably, said
 10 inductor comprises a coil, for example a planar coil.

In some embodiments, for example in which said coupled coil implements an inverting star network of inductive elements, said first and second windings are wound in opposite senses.

15 In some embodiments, said coupled coil implements a non-inverting delta network of inductive elements connected between said second and third ports and said common circuit node. Said non-inverting delta network may comprises a first inductive element connected between said second and third ports, a second inductive element connected between said first and second ports, and a third inductive element connected between said first and third ports. Said first inductive element may have
 20 an inductance of $L_x = (L^2 - M^2)/M$, and said second and third inductive elements each has an inductance of $L + M$, where L and M are the self inductance and mutual inductance, respectively, of the coupled coil. Advantageously, said first and second windings of the coupled coil implement a respective one of said second and third inductive elements.

25 Optionally, said second and third inductive elements are each included in a respective resonator circuit. Each resonator circuit may comprise the respective inductive element in parallel with a capacitor. In some embodiments, said inductive elements of said second port circuit branch and said third port circuit branch each has an inductance that is equal to, or substantially equal to, $0.75(L + M)$, where L and M are the self inductance and mutual inductance, respectively, of the coupled coil.

30 Optionally, each resonator circuit is configured to serve as a second harmonic trap filter.

In some embodiments, for example in which said coupled coil implements a non-inverting delta network of inductive elements, said first and second windings are wound in the same sense.

35 In some embodiments, for example in which said coupled coil implements an inverting star network of inductive elements, a resistor is connected between said first and second windings, preferably between the respective first ends of said first and second windings or between said second and third ports.

In other embodiments, for example in which said coupled coil implements a non-inverting delta network of inductive elements, there is no resistor connected between said first and second windings or between said second and third ports.

- 5 In preferred embodiments, the device comprises a Wilkinson power divider/combiner having a lumped-element circuit topology that includes a respective inductor representing first and second transmission lines. The inductors are advantageously implemented, respectively, by first and second mutually coupled conductive windings of a coupled coil. The device is suitable for implementation in an integrated circuit (IC), where chip area is premium and so the number of circuit components
10 should be minimised.

Advantageously, circuits and devices embodying the invention are relatively small when compared to conventional comparable circuits/devices, and can be designed more quickly.

- 15 Further advantageous aspects of the invention will be apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments and with reference to the accompanying drawings.

Brief Description of the Drawings

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Embodiments of the invention are now described by way of example in which like numerals are used to denote like parts and in which:

- Figure 1 is a schematic diagram of a lumped-element Wilkinson power divider / combiner circuit;
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Figure 2 is a schematic diagram of an alternative lumped-element Wilkinson power divider / combiner circuit;

- Figure 3 is a schematic diagram of circuits representing a coupled coil, in particular an inverting-
30 coupled coil;

Figure 4 is a schematic diagram of a lumped-element Wilkinson power divider / combiner circuit including a star configured inductor network modelling a single inverting coupled coil;

- 35 Figure 5 is a schematic diagram of the lumped-element Wilkinson power divider / combiner circuit of Figure 4, including a second harmonic trap resonator;

Figure 6 is a circuit layout diagram suitable for implementing the circuit of Figure 4;

- 40 Figure 7 is a circuit layout diagram suitable for implementing the circuit of Figure 5;

Figure 8 is a schematic diagram of alternative circuits representing a coupled coil, in particular a non-inverting coupled coil;

Figure 9 is a schematic diagram illustrating the transformation of a star configured inductor network to a delta configured inductor network, in particular a non-inverting star network to a non-inverting delta network;

Figure 10 is a schematic diagram of a lumped-element Wilkinson power divider / combiner circuit including a delta configured inductor network modelling a single coupled coil, in particular a single non-inverting single coupled coil;

Figure 11 is a schematic diagram of the lumped-element Wilkinson power divider / combiner circuit of Figure 10, further including second harmonic trap resonators;

Figure 12 is a circuit layout diagram suitable for implementing the circuit of Figure 10; and

Figure 13 is a circuit layout diagram suitable for implementing the circuit of Figure 11.

Detailed Description of the Drawings

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Figure 1 a schematic diagram of a lumped-element power divider / combiner circuit 10 of a type commonly referred to as a Wilkinson circuit. The circuit 10 has three ports P1, P2, P3. When the circuit 10 is acting as a power divider, port P1 is an input port, and ports P2 and P3 are output ports. In use, an input signal received at P1 provides corresponding output signals at P2 and P3, the power of the input signal being divided between the output signals. When the circuit 10 is acting as a power combiner, port P1 is an output port, and ports P2 and P3 are input ports. In use, input signals received at P2 and P3 generates a corresponding output signal at P1, the power of the input signals being combined in the output signal. Hence, port P1 may serve as a single input port or a combined output port.

30

A classical implementation of a Wilkinson circuit comprises two identical quarter-wavelength transmission lines (QWTL) with a resistor R connected between the two circuit branches. When implemented at low microwave frequencies (e.g. below 20 GHz), the physical length of the transmission lines is relatively large, e.g. at 5 GHz the length is 7.6 mm, assuming a relative permittivity of 3.9 for SiO₂, which can be problematic especially in applications where the circuit is to be implemented in an IC. A solution to this problem is to replace each transmission line with an equivalent lumped-element circuit model. In the example of Figure 1, each transmission line is modelled as a series inductor L connected between two shunt capacitors C. Figure 2 shows a schematic diagram of an alternative Wilkinson lumped-element power divider / combiner circuit 10'. The sole difference between circuit 10 and circuit 10' is that the two grounded capacitors C connected to P2 and P3 of circuit 10 are replaced with a single differential capacitor C of circuit 10'.

The other two grounded capacitors C connected to P1 of circuit 10 are in parallel and therefore can be combined into a single grounded capacitor 2C that is identical to that in circuit 10'. Values for the components of the circuits 10, 10' may be determined using any conventional method.

- 5 The ports P1, P2, P3 are shown connected to a respective termination impedance, which is assumed by way of example to comprise a 50Ω resistance.

It will be understood that other circuit topologies may be used to implement lumped-element power divider / combiner circuits. A common feature of such circuits is the presence of a respective inductor
10 for each transmission line, i.e. in each circuit branch that models a respective transmission line.

In preferred embodiments, a power divider / combiner circuit is implemented in an IC. The circuit may comprise the topology shown in Figures 1 or 2, or in Figures 4, 5, 10 or 11 described hereinafter, or may have an alternative topology, especially a Wilkinson power divider / combiner
15 circuit topology. In order to reduce the area (space) required in an IC to implement the circuit, the respective inductor L of each branch of the divider/combiner circuit are both realised using a coupled coil structure, i.e. the same coupled coil structure implements each inductor L. In preferred embodiments, two inductors L, each being part of a respective transmission line model, are realised by a coupled coil structure. In preferred embodiments, the coupled coil structure (which may also be
20 referred to as a coupled coil) comprises first and second mutually coupled conductive windings (or coils), i.e. conductive windings that are coupled for mutual inductance. It will be understood that mutual inductance occurs during use, i.e. when the windings (coils) are energised, the windings being located in proximity with one another to allow mutual inductance. The coupled coil structure may comprise a centre-tapped inductor structure, i.e. a coil structure with a third port provided
25 between its end ports, typically in the middle. Advantageously, the coupled coil structure is provided as a single component (which may be referred to as a single coupled coil structure, or single coupled coil). The preferred single coupled coil structure comprises two windings configured for mutual inductance and incorporated into the same component (i.e. an IC component in preferred embodiments). The implementation of first and second mutually coupled windings in a single coil
30 structure component allows first and second inductances (i.e. the two series inductances L in Figure 2 in this example) to be provided with in a smaller physical area within an IC in comparison with implementation of inductor coils as separate components.

The left side of Figure 3 is a schematic representation of a coupled coil structure, in particular an
35 inverting coupled coil structure, comprising two inductive elements L that are inductively coupled with each other, having a mutual inductance M, and being wound in opposite senses. As illustrated on the right of Figure 3, the coupled coil structure can be modelled as a star network of inductive elements (or inductors). The star network has three circuit branches, each comprising a respective inductive element, and each having one end connected to a common electrical circuit node, the respective
40 other end being free for connection to the surrounding circuitry/components. As shown in Figure 3, the value of the inductances in each branch of the star network are $L+M$, $L+M$, and $-M$ respectively,

where L and M are the self inductance and mutual inductance of the coupled coil structure, respectively.

Figure 4 is a schematic diagram of a lumped-element Wilkinson power divider / combiner circuit 110 embodying one aspect of the invention, in which a star network 114 (an inverting star network in this example) of inductive elements 112a, 112b, 112c is provided for implementation by a single coupled coil structure. The circuit 110 has three circuit branches B1, B2, B3, connected between a respective one of the ports P1, P2, P3 and a common circuit node CN. The coupled coil structure provides part of the implementation of the transmission lines of the Wilkinson circuit, as described above. In particular, the star network 114 is incorporated into the circuit 110 such that the inductive element 112b is included in the branch B2 of the circuit 110 that is connected to port P2, the inductive element 112c is included in the branch B3 of the circuit 110 that is connected to port P3, and the inductive element 112a is connected between the common circuit node CN and an internal node N of the star network 114. The values of the inductances 112a, 112b, 112c in each branch of the star network 114 are $-M$, $L+M$ and $L+M$, respectively, where L and M are the self inductance and mutual inductance of the coupled coil structure, respectively.

To compensate for the negative inductance $-M$ of element 112a of the star network 114, the circuit 110 includes an inductive element 112d. The inductive element 112d may be connected in series with inductive element 112a of the star network 114 and preferably has an inductance $+M$, or substantially $+M$, to cancel or substantially cancel the inductance $-M$ of inductive element 112a. Advantageously, the additional inductive element 112d is implemented as a coil (preferably with an inductance value of $+M$). The coil 112d is typically implemented as a component that is separate from the single coupled coil component provided for implementing inductive elements 112a, 112b, 112c. The component for implementing coil 112d is conveniently incorporated into branch B1 of the circuit 110, preferably in series between port P1 and inductive element 112a of the star network 114. Without the additional inductive element 112d the return loss at the ports P1, P2, P3 and the isolation between the ports P2, P3 degrades substantially.

Figure 5 is a schematic diagram of a lumped-element Wilkinson power divider / combiner circuit 110' embodying one aspect of the invention. The circuit 110' is similar to the circuit 110 of Figure 4, like numerals being used to denote like parts and the same or similar description applying as would be apparent to a skilled person. To compensate for the negative inductance $-M$ of inductive element 112a of the star network 114, the circuit 110' includes a resonator 116 comprising an inductive element 116a and capacitive element 116b in parallel. The resonator 116 may be connected in series with inductive element 112a of the star network 114. The parallel LC resonator 116 serves as a second harmonic trap filter. As a result, the total harmonic distortion (THD) level of the combined output signal (at port P1 assuming that the circuit 110' is operating as a power combiner) is significantly decreased. At the fundamental, or operating, frequency f_0 the second harmonic trap 116 will present a net inductance of $+M$. Advantageously, however, the value of the inductance of the inductive element 116a is $0.75M$ (a 25% reduction compared to the inductive element 112d of Figure

4). In preferred embodiments, the inductive element 116a is implemented as a coil. The coil 116a is typically implemented as a component that is separate from the single coupled coil component provided for implementing inductive elements of star network 114. The resonator 116 is conveniently incorporated into branch B1 of the circuit 110', preferably in series between port P1 and element
 5 112a of the star network 114. In preferred embodiments, the lower inductance value (0.75M) of the coil 116a allows it to be smaller than the coil 112d of the circuit 110.

Component values for the resonator 116 may be determined in any suitable conventional manner. For example, the resonant frequency may be defined as the frequency at which a resonator
 10 resonates and ideally forms an open circuit when in a parallel LC configuration. At frequencies below the resonant frequency, the resonator is inductive. In the present example, it is desired to have the resonator 116 resonate at the second harmonic frequency $2f_0$, i.e. twice the fundamental frequency, to block second harmonic signals while still providing the inductance +M at f_0 .

15 Values of the other components (e.g. C1 and C2) of circuits 110, 110' may be determined using any convenient conventional technique, e.g. even/odd mode analysis. It is noted that, in the illustrated examples of Figures 4 and 5, C1 is equal to 2C as shown in Figure 2, and C2 is equal to C as shown in Figure 2.

20 In preferred embodiments, the resonator is a parallel LC resonator connected in series with network 114. In alternative embodiments, the resonator may take any other suitable form and may be connected in series or parallel or shunt as required. For example a series LC resonator may be connected in shunt with port P1. In this alternative arrangement, the element 112d of Fig. 4 is still
 25 provide the required series inductance +M at f_0 .

Figures 6 and 7 show preferred circuit layouts for implementing, respectively, circuits 110 and 110' to create a power combiner/divider device. In preferred embodiments the circuits 110, 110' are implemented in an IC. The IC may take any conventional form. It will be understood that the resulting
 30 device may act as a power combiner or a power divider depending on how it is used and/or incorporated into another circuit or system (not illustrated). It is noted that the termination impedances are omitted from Figures 6 and 7.

Referring firstly to Figure 6, the circuit 110 comprises a coupled coil structure 118 having first and
 35 second electrically conductive windings 118A, 118B. Each winding 118A, 118B has a respective first end 120A, 120B and a respective second end 122A, 122B. Each winding 118A, 118B may be shaped to define at least one turn between its ends 120A, 122A; 120B, 122B. Typically the windings 118A, 118B are flat, i.e. spiral and are typically also co-planar with each other. Alternatively, the windings 118A, 118B may have other forms and/or arrangements, e.g. each winding 118A, 118B
 40 may be a toroidal coil.

The coupled coil structure 118 is advantageously provided as a single IC component that comprises both windings 118A, 118B. It is noted that the windings 118A, 118B may alternatively be referred to as windings of the coupled coil structure 118.

- 5 In preferred embodiments, the windings 118A, 118B are wound in opposite senses (i.e. clockwise or anti-clockwise). In the illustrated example, winding 118A is wound anti-clockwise from its first end 120A to its second end 122A, while winding 118B is wound clockwise from its first end 120B to its second end 122B, although the opposite arrangement may alternatively be used. The arrangement is such that, in use, current flowing in adjacent portions of the respective windings 118A, 118B flow
- 10 in opposite directions (i.e. the current flowing in any given portion of winding 118A flows in an opposite direction to the current flowing in an adjacent portion of winding 118B). As such, the mutual coupling between the windings 118A, 118B may be described as an inverting coupling, and the coil structure 118 may be described as an inverting coupled coil structure.
- 15 The windings 118A, 118B are located in proximity with one another such that, in use, they are coupled by mutual inductance. Typically, the windings 118A, 118B are interspersed with one another, e.g. such that one or more turns of each winding 118A, 118B is located between one or more turns of the other winding 118B, 118A.
- 20 The first end 120A of winding 118A is connected to port P2. The connection may be a direct electrical and physical connection. Optionally, the first end 120A of winding 118A may serve as port P2. The first end 120B of winding 118B is connected to port P3. The connection may be a direct electrical and physical connection. Optionally, the first end 120B of winding 118B may serve as port P3. The second ends 122A, 122B of the windings 118A, 118B are electrically connected together. In
- 25 the illustrated embodiment, the second ends 122A, 122B are interconnected at circuit node CN. Each winding 118A, 118B corresponds with a respective branch B2, B3 of the circuit 110. In particular, the windings 118A, 118B are configured to provide the inductance $L+M$ in circuit branches B2, B3, and the inductance $-M$ in circuit branch B1, where L and M are the self inductance and mutual inductance of the coupled coil structure 118.
- 30 In preferred embodiments the first ends 120A, 120B of the winding 118A, 118B are located at a first side of the coupled coil structure 118, the second ends 122A, 122B being located at the opposite side of the coil structure 118. As such, each winding 118A, 118B typically does not comprise a whole number of turns. In the illustrated embodiment, each winding 118A, 118B comprises 1.5 turns
- 35 between ends. In similar embodiments, each winding 118A, 118B may comprise at least one whole turn and a half turn between ends. In alternative embodiments, the first and second ends of the windings may be on the same side of the coupled coil structure, in which case each winding may comprise a whole number of turns. Preferably, the windings 118A, 118B are of the same (or substantially the same) length.

The windings 118A, 118B may be formed as conductive tracks or any other convenient electrical conductor supported by the IC. Typically, the windings 118A, 118B are formed in a conductive (usually metallic) layer of the IC, preferably in the thickest conductive layer. To facilitate the preferred interspersing of the windings 118A, 118B, one or more segments S1, S2 of either one or both
5 windings 118A, 118B (as required) may be formed in a second conductive layer of the IC, typically using one or more conductive vias V1 to form an electrical connection between layers.

An electrical connector 124 is connected to the common circuit node CN for connecting the CN to the inductive element 112d, which in preferred embodiments comprises a coil. The connector 124
10 may be provided in a different layer of the IC than the windings 118A, 118B and the coil 112d, e.g. a third conductive layer in this example, and so one or more conductive vias V2, V3 may be provided to form an electrical connection between layers as required.

The coil 112d may be shaped to define one or more turn between its ends 126, 128. Alternatively,
15 the coil 112d may comprise only part of one turn, e.g. 0.5 turns or 0.75 turns. The number of turns/partial turns may depend on the compensating inductance required and/or the coupling factor of the coil. The coil 112d may be flat, e.g. spiral, or may take any other convenient form, e.g. toroidal.

The first end 126 of coil 112d is connected to port P1. The connection may be a direct electrical and
20 physical connection. Optionally, the first end 126 of coil 112d may serve as port P1. The second end 128 of the coil 112d is electrically connected to the circuit node CN (by connector 124 in this example). The coil 112d provides part of the branch B1 of the circuit 110.

The coil 112d typically does not comprise a whole number of turns. In the illustrated embodiment,
25 each the coil 112d comprises 2.5 turns between ends. More generally, the coil 112d may comprise at least one whole turn and a half turn between ends. In preferred embodiments the coil 112d has an inductance that is equal, or substantially equal, to +M.

The coil 112d may be formed as a conductive track or any other convenient electrical conductor
30 supported by the IC. The coil 112d may be formed in the same conductive layer of the IC as the windings 118A, 118B.

In preferred embodiments, the coil 112d is located adjacent to the coupled coil structure 118, the coil
35 112d and coupled coil structure 118 being located between port P1 and ports P2, P3.

The other components of the circuit 110 may be connected to the coil 112d and coupled coil structure 118 as required by the circuit topology, and may be implemented in any form supported by the IC or other implementation media. Conveniently, these other components are connected to one or more of the ports P1, P2, P3 as applicable. In the present embodiment, a capacitor C2 and
40 resistor R are connected in parallel between ports P2 and P3. Circuit branch B1 includes a shunt capacitor C1 connected between port P1 and RF ground.

Referring now to Figure 7, the preferred implementation of circuit 110' is the same as that of the circuit 110 shown in Figure 6 in respect of circuit branches B2 and B3, and the same description applies with the same reference numerals being used. However, instead of coil 112d, circuit 110' includes the resonator 116 connected between the port P1 and the common circuit node CN. The resonator 116 includes inductor 116a which is typically implemented as an electrically conductive coil. The coil 116a may be the same as the coil 112d of Figure 6 (the same description applying and the same reference numerals being used) except that its inductance may be lower, and so the coil 116a may be physically smaller than coil 112d. In preferred embodiments the coil 116a has an inductance with a magnitude that is three quarters of, or approximately three quarters of, the inductance M.

The capacitor C3 of the resonator 116 may be connected in parallel with the coil 116a, and may be implemented in any form supported by the IC or other implementation media. Conveniently, the capacitor C3 is connected between the ends 126, 128 of the coil 116a. The capacitor C1 may be connected between the first end 126 of the coil 116a and ground.

In preferred embodiments, the coil 116a is located adjacent to the coupled coil structure 118, the coil 116a and coupled coil structure 118 being located between port P1 and ports P2, P3.

In the illustrated embodiments, the resonator 116 is tuned to the second harmonic, i.e., $f_r = 2f_0$, to act as a second harmonic trap. In alternative embodiments, the resonator may be configured as an n^{th} harmonic resonator (i.e., $f_r = nf_0$), in which the coil 116a would have an inductance of $(n^2-1)/n^2 M$ rather than $3/4 M$.

In arriving at the invention embodied by the devices of Figures 6 and 7, the presence of the $112a (-M)$ inductance has been identified as a result of implementing the two series inductors of a Wilkinson circuit with a coupled coil structure, in particular an inverting coupled coil structure in a star configuration. If the $-M$ inductance is not taken into account in the design, the resulting circuit will exhibit (i) poor isolation between ports P2 and P3, and (ii) poor impedance matching at all ports P1, P2, P3. Poor isolation poses detrimental loading effects to the power amplifiers (PAs). This means that the PAs and Wilkinson combiner cannot be optimised independently, and as a result, it requires time-consuming co-design efforts with considerable performance penalty.

A disadvantage of using a star network coupled coil structure (as illustrated in Figures 4 and 5) is the inaccessibility of the internal node N shared by the three inductances $L+M$, $L+M$, and $-M$. If such access is available, the second harmonic trap can be more effectively incorporated into the Wilkinson circuit by replacing each of the $L+M$ inductances with a parallel LC resonator. Since $L+M > M$, more chip area can be saved.

The coupled coil structure 118 depicted in Figures 6 and 7 implements an inverting star network coupled coil with elements of $L+M$, $L+M$, and $-M$, in which the windings 118A, 118B are wound such that the currents in the adjacent windings 118A, 118B flow in opposite directions (anti-clockwise and clockwise). As an alternative, it is possible to wind the windings of a coupled coil structure in the same direction, or sense, such that the currents in adjacent windings (or in adjacent portions of adjacent windings) flow in the same direction. The left side of Figure 8 is a schematic representation of a non-inverting coupled coil structure, comprising two inductive elements L that are inductively coupled with each other, having a mutual inductance M , and being wound in the same sense. As illustrated on the right of Figure 8, the coupled coil structure can be modelled as a star network of inductive elements (or inductors). The star network has three circuit branches, each comprising a respective inductive element, and each having one end connected to a common electrical circuit node, the respective other end being free for connection to the surrounding circuitry/components. As shown in Figure 8, the values of the inductances in each branch of the non-inverting star network are $L-M$, $L-M$, and M respectively, where L and M are the self inductance and mutual inductance of the coupled coil structure, respectively. The resulting $L-M$ inductances imply that the magnetic fields induced by the adjacent currents flowing in the coupled windings are being added destructively as opposed to constructively ($L+M$), which is the case for the arrangement shown in Figure 3.

A star to delta transformation may be used to transform the star circuit shown in Figure 8 to an equivalent delta circuit, as illustrated in Figure 9, which illustrates in particular transformation of a non-inverting star network into a non-inverting delta network. The delta equivalent circuit comprises three inductive elements $L+M$, $L+M$, and $L_x = (L^2 - M^2)/M$, where L and M are the self-inductance and mutual inductance, respectively, of the coupled windings. The component values of the delta non-inverting coupled coil $L+M$, $L+M$, and L_x can be obtained in any conventional manner, for example by star-to-delta conversion or directly from the ABCD transmission parameters of the non-inverting coupled coil.

The component values of the star inverting coupled coil $L+M$, $L+M$, and $-M$ (Fig. 3) and the star non-inverting coupled coil $L-M$, $L-M$, and M (Fig. 8) may be obtained from the ABCD transmission parameters of the inverting and non-inverting coupled coils, respectively. Using a similar technique, the component values of the delta non-inverting coupled coil (Fig. 9) can be obtained.

Figure 10 is a schematic diagram of a lumped-element Wilkinson power divider / combiner circuit 210 embodying one aspect of the invention, in which a delta network 214 of inductive elements 212a, 212b, 212c connected end-to-end is provided for implementation as a single non-inverting coupled coil. The circuit 210 has port P1, and circuit branches B2, B3, the branches B2, B3 being connected between a respective port P2, P3 and a common electrical circuit node CN (which in this embodiment corresponds to a point between inductive elements 212b and 212c of the delta network 214). The coupled coil structure 214 provides part of the implementation of the transmission lines of the Wilkinson circuit, as described above. In particular, the delta network 214 is incorporated into the circuit 210 such that the inductive element 212b is included in the branch B2 of the circuit 210 that

includes port P2, the inductive element 212c is included in the branch B3 that includes port P3, and the inductive element 212a is connected between branches B2 and B3. The values of the inductances 212a, 212b, 212c in each branch of the delta network 214 are L_x , $L+M$ and $L+M$, respectively, where L and M are the self inductance and mutual inductance of the coupled coil structure, respectively, and $L_x = (L^2 - M^2)/M$.

The capacitor C1 in Figures 10 and 11 is equal to $2C$ as shown in Figure 2. The capacitor C2 in Figures 10 and 11 represents the total capacitance of the capacitor C in Figure 2 and the capacitance required to tune out L_x in order to provide an open circuit at the fundamental frequency.

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Significantly, the ballast resistor R (which is shown in each of Figures 1, 2, 4 and 5 as the 100Ω resistor, and in Figures 6 and 7 as resistor R connected between ports P2, P3) that is normally required in a conventional implementation of a Wilkinson circuit can be omitted. This is because there is a parasitic series resistance (not illustrated) with inductive element 212a, which can be used to provide the function of the conventional ballast resistor R without requiring an additional resistor component to be provided (e.g. resistor R connected between the second and third ports P2, P3 in Figures 6 and 7 can be omitted). Hence, the delta type coupled coil structure can be designed to obviate the need for a separate ballast resistor in the circuit 210. In particular this may be achieved by appropriate selection of the coupling factor k of the coupled coil structure. By way of example, for the coupled coil structure of Figure 12, designing the coil structure such that $k = 0.72$ allows the conventional ballast resistor of 100Ω to be omitted.

Figure 11 is a schematic diagram of a lumped-element Wilkinson power divider / combiner circuit 210' embodying one aspect of the invention. The circuit 210' is similar to the circuit 210 of Figure 10, like numerals being used to denote like parts and the same or similar description applying as would be apparent to a skilled person. Unlike the circuit 210, the circuit 210' includes respective resonator 216 replacing the $L+M$ inductive elements 212b, 212c. Each resonator 216 preferably comprises an inductive element 216a and capacitive element 216b in parallel. The resonators 216 serve as second harmonic trap filters. Advantageously, this arrangement allows the inductance value of inductive element 216a to be lower than the inductance value of elements 212b, 212c of circuit 210 (reduced to $0.75(L+M)$ from $L+M$ in the preferred embodiment). The circuit 210', compared to circuit 210, has a much lower THD, meaning a less distorted output signal. In alternative embodiments, the resonators may be configured to act as an n^{th} harmonic resonator (i.e., $f_r = nf_0$) and the inductance value of element 216a may be selected accordingly, in which case element 216a has an inductance of $(n^2 - 1)/n^2 (L+M)$ rather than $0.75(L+M)$.

Figures 12 and 13 show preferred circuit layouts for implementing, respectively, circuits 210 and 210' to create a power combiner/divider device using standard CMOS technology. In preferred embodiments the circuits 210, 210' are implemented in an IC. The IC may take any conventional form. It will be understood that the resulting device may act as a power combiner or a power divider

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depending on how it is used and/or incorporated into another circuit or system (not illustrated). It is noted that the termination impedances are omitted from Figures 12 and 13.

Referring firstly to Figure 12, the circuit 210 comprises a non-inverting coupled coil 218 having first and second electrically conductive windings 218A, 218B. Each winding 218A, 218B has a respective first end 220A, 220B and a respective second end 222A, 222B. Each winding 218A, 218B may be shaped to define at least one turn between its ends 220A, 222A; 220B, 222B. Typically the windings 218A, 218B are flat, i.e. spiral, and are typically also co-planar with each other. Alternatively, the windings 218A, 218B may have other forms and/or arrangements, e.g. each winding 218A, 218B may be a toroidal coil.

The coupled coil structure 218 is advantageously provided as a single IC component that comprises both windings 218A, 218B. It is noted that the windings 218A, 218B may alternatively be referred to as windings of the coupled coil structure 218.

In preferred embodiments, the windings 218A, 218B are wound in the same sense (i.e. clockwise or anti-clockwise). In the illustrated example, the windings 218A, 218B are wound anti-clockwise from their first end 220A, 220B to their second end 222A, 222B, although the opposite arrangement may alternatively be used.

The windings 218A, 218B are located in proximity with one another such that, in use, they are coupled by mutual inductance. Typically, the windings 218A, 218B are interspersed with one another, e.g. such that one or more turns of each winding 218A, 218B is located between one or more turns of the other winding 218B, 218A.

The first end 220A of winding 218A is connected to port P2. The connection may be a direct electrical and physical connection. Optionally, the first end 220A of winding 218A may serve as port P2. The first end 220B of winding 218B is connected to port P3. The connection may be a direct electrical and physical connection. Optionally, the first end 220B of winding 218B may serve as port P3. The second ends 222A, 222B of the windings 218A, 218B are electrically connected together. In the illustrated embodiment, the second ends 222A, 222B are interconnected at circuit node CN. Each winding 218A, 218B provides a respective branch B2, B3 of the circuit 210. The windings 218A, 218B are configured to provide the inductance $L+M$ in circuit branches B2, B3, and the inductance L_x between circuit branches B2 and B3, where L and M are the self inductance and mutual inductance of the coupled coil structure.

The first ends 220A, 220B of the windings 218A, 218B may be located at opposite sides of the coupled coil structure 218A, 218B, typically diametrically opposite each other, or substantially diametrically opposite each other. The second ends 222A, 222B may be located in a central region of the coil structure 218, optionally line with the respective first end 220A, 220B. Each winding 218A, 218B may comprise a whole number of turns, or substantially a whole number of turns. In the

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illustrated embodiment, each winding 218A, 218B comprises 2 turns between ends. More generally, each winding 218A, 218B may comprise one or more whole turn between ends, or half of one turn, or at least one whole turn and half a turn. Preferably, the windings 218A, 218B are of the same (or substantially the same) length.

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The windings 218A, 218B may be formed as conductive tracks or any other convenient electrical conductor supported by the IC. Typically, the windings 218A, 218B are formed in a conductive (typically metallic) layer, preferably the thickest conductive layer, of the IC.

10 The common circuit node CN of the windings 218A, 218B is connected to port P1, typically by an electrical connector 224. The connector 224 may be provided in a different layer of the IC than the windings 218A, 218B, e.g. in second conductive layer in this example, and so one or more conductive vias V2, V3 may be provided to form an electrical connection between layers as required.

15 The other components of the circuit 210 may be connected to the coupled coil 218 as required by the circuit topology, and may be implemented in any form supported by the IC or other implementation media. In the present embodiment, a capacitor C2 is connected between ports P2 and P3. This may be achieved by connecting the capacitor C2 between the first and second windings 218A, 218B, conveniently between their first ends 220A, 220B. A shunt capacitor C1 is connected between port
20 P1 and RF ground.

Referring now to Figure 13, the preferred implementation of circuit 210' is the same as that of the circuit 210 shown in Figure 12, and the same description applies with the same reference numerals being used unless otherwise indicated. To implement the resonators 216, a respective capacitor C3
25 is connected between ports P1 and P2, and between the ports P1 and P3 (the inductive part 216a of the resonators 216 being provided by the windings 218A, 218B). In preferred embodiments the element 216a has an inductance with a magnitude that is three quarters of, or approximately three quarters of, the magnitude of the inductance of elements 212b, 212c of Figure 10.

30 The respective capacitor C3 of the resonators 216 may be connected to the coil structure 218 and may be implemented in any form supported by the IC or other implementation media. Conveniently, each capacitor C3 is connected between the respective first end 220A, 220B of the respective winding 218A, 218B and the common circuit node CN, conveniently via connector 224. The capacitor C1 may be connected between the coil structure 218 (typically from the common circuit node CN)
35 and ground, conveniently via connector 224.

In preferred embodiments, in circuit 210', the windings 218A, 218B are configured to provide the inductance $0.75(L+M)$ in circuit branches B2, B3, and the inductance L_x between circuit branches B2 and B3, where L and M are the self inductance and mutual inductance of the coupled coil structure.

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The devices 210, 210' provide a very compact implementation of a Wilkinson power divider/combiner. Device 210 requires only three components, i.e. a delta type non-inverting coupled coil structure and two capacitors C1, C2, while device 210' requires two additional components, namely capacitors C3. This translates into a significantly reduced chip area, and consequently, cost.

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Preferred embodiments of the invention offer any one or more of the following advantages in comparison with conventional products: a compact design with smaller chip area and fewer components; a simplified optimisation process, shorter design time, and faster time to market; enhanced circuit performances in terms of the impedance matching at all ports and the isolation

10 between the two branches B2, B3; added filtering functionality resulting in less distorted output signal since the unwanted second-harmonic component is substantially attenuated.

Embodiments of the invention are particularly suited for implementation in an IC for example using CMOS technology, and are for example particularly suited for use in wireless portable devices

15 operating at frequencies below 20 GHz (e.g. Wi-Fi, Bluetooth, ZigBee, mobile phones, commercial and military radar systems, etc.).

The invention is not limited to the embodiment(s) described herein but can be amended or modified without departing from the scope of the present invention.

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CLAIMS:

1. A power combiner or power divider device comprising:
 - a first port;
 - 5 a second port;
 - a third port, and
 - a common circuit node between said first, second and third ports,wherein said second port is connected to said common circuit node by second port circuit branch comprising at least one inductive element, and said third port is connected to said common circuit
10 node by a third port circuit branch comprising at least one inductive element, and wherein at least one inductive element of said second port circuit branch and at least one inductive element of said third port circuit branch are implemented, respectively, by first and second mutually coupled conductive windings of a coupled coil.
- 15 2. The device of claim 1, wherein each of said first and second windings has a respective first end and a respective second end, each winding being shaped to define at least part of one turn, typically one or more turns, between its first and second ends.
3. The device of claim 1 or 2, wherein each of said first and second windings is planar, and wherein,
20 preferably, said first and second windings are co-planar with one another.
4. The device of any preceding claim, wherein said first and second windings are interspersed with one another such that one or more turns, or part of a turn, of each winding is located between one or more turns, or part of a turn, of the other winding.
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5. The device of any preceding claim, wherein a capacitor is connected between said second port and said third port, said capacitor conveniently being connected between the first and second windings, preferably between a respective first ends of each winding.
- 30 6. The device of any preceding claim, wherein said first port is connected to said common circuit node by a first port circuit branch comprising at least one inductive element, and wherein, preferably, said first port circuit branch includes a shunt capacitor connected between said first port and RF ground.
- 35 7. The device of claim 6, wherein said coupled coil implements an inverting star network of inductive elements connected between said second and third ports and said common circuit node.
8. The device of claim 7, wherein said inverting star network comprises a first inductive element connected between said common circuit node and an internal node of the star network, a second
40 inductive element connected between said second port and said internal node, and a third inductive

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element connected between said third port and said internal node, and wherein said first and second windings of the coupled coil implement a respective one of said second and third inductive elements.

9. The device of claim 8, wherein said first inductive element has an inductance of $-M$, and said second and third inductive elements each has an inductance of $L+M$, where L and M are the self inductance and mutual inductance, respectively, of the coupled coil.

10. The device of any one of claims 6 to 9, wherein said first port circuit branch comprises an inductor between said first port and said common circuit node, preferably being connected in series between said first port and said common circuit node.

11. The device of claim 10, wherein said inductor has an inductance that is equal to, or substantially equal to, the mutual inductance M between said first and second windings.

12. The device of claim 11, wherein said inductor is included in a resonator circuit that is connected between said first port and said common circuit node, and wherein said resonator circuit may comprise said inductor in parallel with a capacitor.

13. The device of any one of claims 12, wherein said inductor has an inductance that is equal to, or substantially equal to, three quarters of the mutual inductance M between said first and second windings.

14. The device of any one of claims 10 to 13, wherein said inductor comprises a coil, conveniently a planar coil.

15. The device of any preceding claim, wherein said first and second windings are wound in opposite senses.

16. The device of any one of claims 1 to 6, wherein said coupled coil implements a non-inverting delta network of inductive elements connected between said second and third ports and said common circuit node.

17. The device of claim 16, wherein said non-inverting delta network comprises a first inductive element connected between said second and third ports, a second inductive element connected between said first and second ports, and a third inductive element connected between said first and third ports, wherein said first and second windings of the coupled coil implement a respective one of said second and third inductive elements.

18. The device of claim 17, wherein said first inductive element has an inductance of $L_x = (L^2 - M^2)/M$, and said second and third inductive elements each has an inductance of $L+M$, where L and M are the self inductance and mutual inductance, respectively, of the coupled coil.

19. The device of claim 17 or 18 wherein said second and third inductive elements are each included in a respective resonator circuit, and wherein, optionally, each resonator circuit comprises the respective inductive element in parallel with a capacitor.

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20. The device of claim 19, wherein said inductive elements of said second port circuit branch and said third port circuit branch each has an inductance that is equal to, or substantially equal to, $0.75(L+M)$, where L and M are the self inductance and mutual inductance, respectively, of the coupled coil.

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21. The device of any one of claims 12, 13, 19 or 20, wherein each resonator circuit is configured to serve as a harmonic trap filter, optionally a second harmonic trap filter.

22. The device as claimed in any one of claims 1 to 6 or 16 to 20, wherein said first and second
15 windings are wound in the same sense.

23. The device as claimed in any one of claims 1 to 15, wherein a resistor is connected between said first and second windings, preferably between the respective first ends of said first and second windings or between said second and third ports.

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24. The device of any one of claims 1 to 6 or 16 to 20, wherein there is no resistor connected between said first and second windings or between said second and third ports.

25. The device of any preceding claim, said at least one inductive element of said second port circuit
25 branch, and said at least one inductive element of said third port circuit branch are a lumped-element representation of a respective transmission line of the power divider or power combiner device.

26. The device of any preceding claim, wherein said coupled coil comprises a single coupled coil structure.

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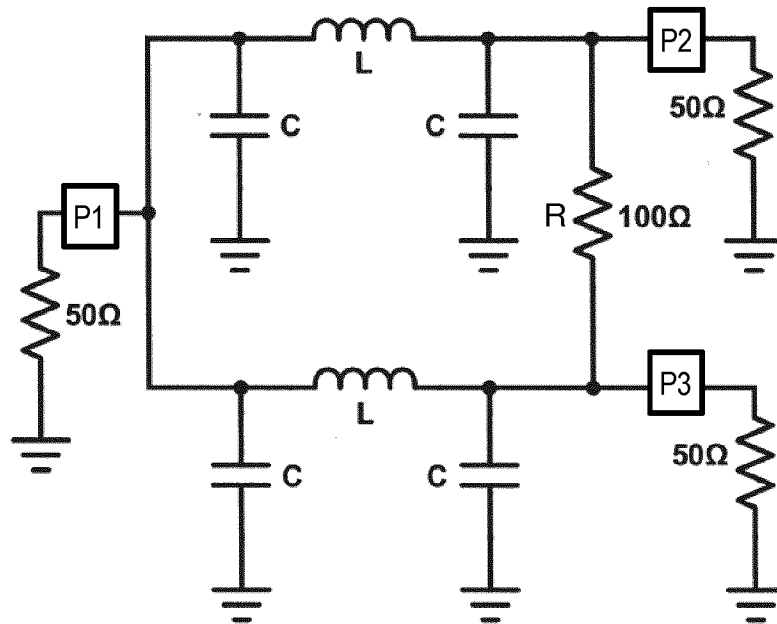


Fig. 1

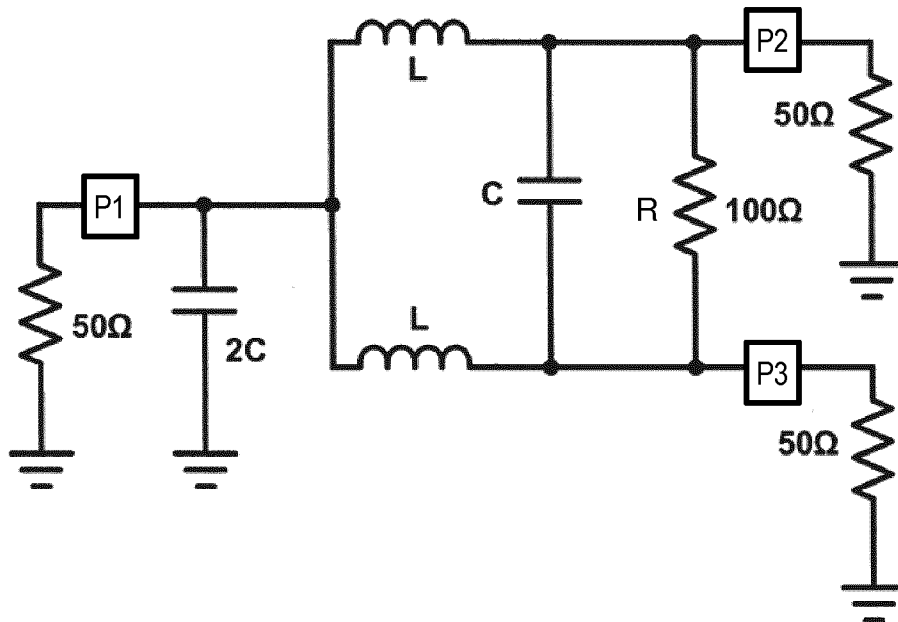


Fig. 2

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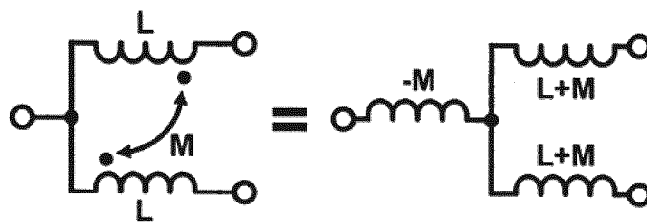


Fig. 3

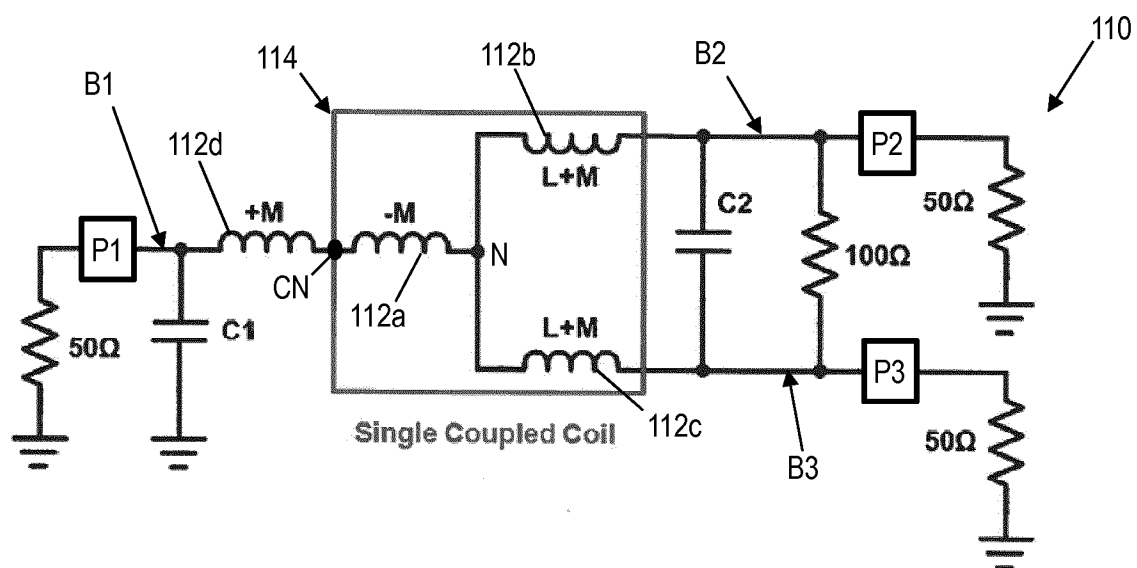


Fig. 4

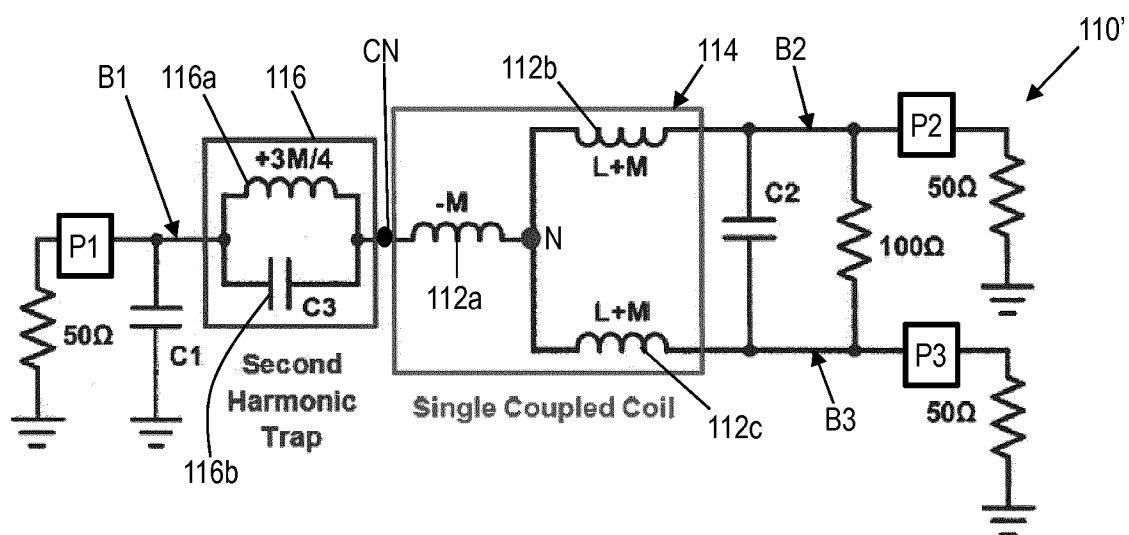


Fig. 5

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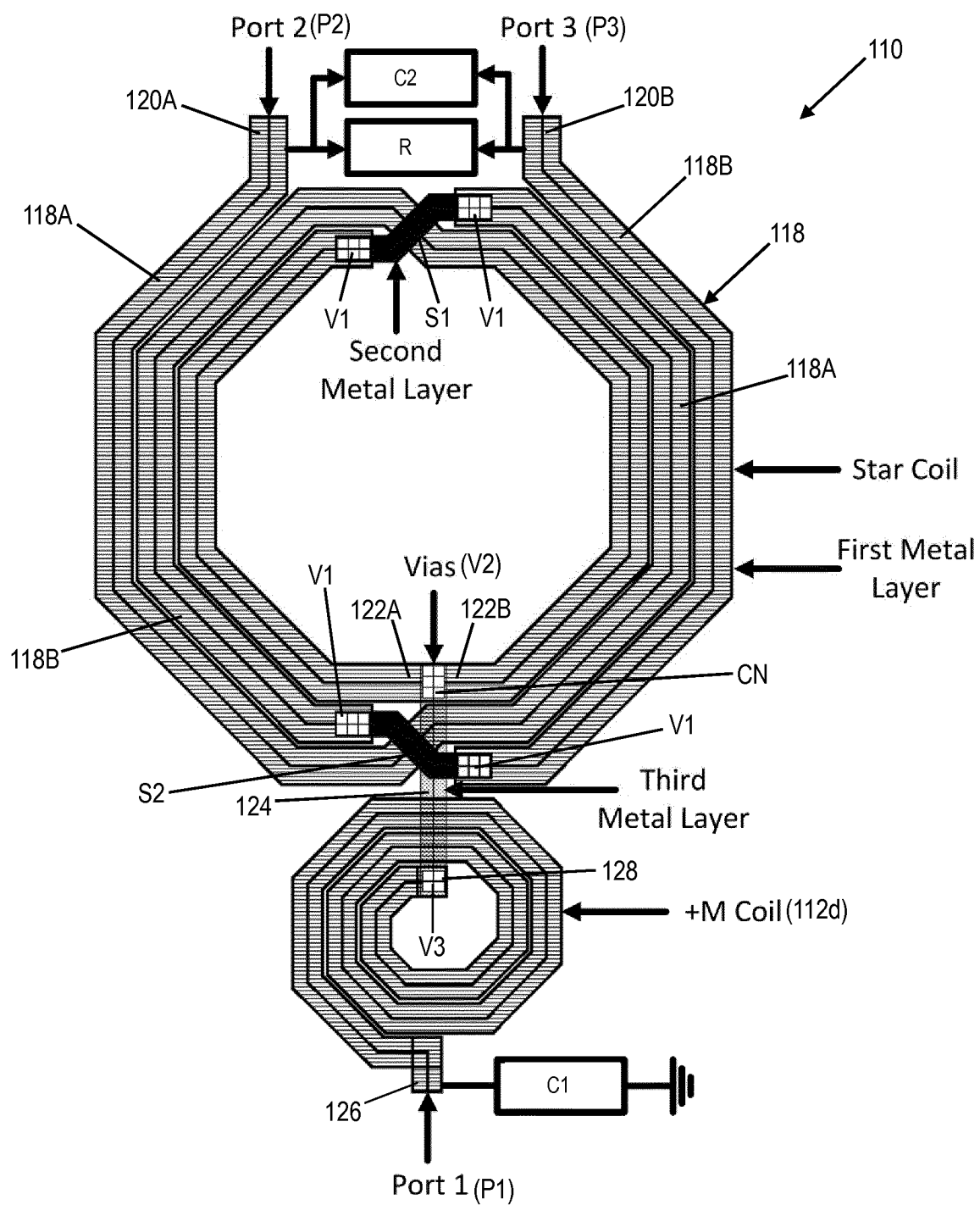


Fig. 6

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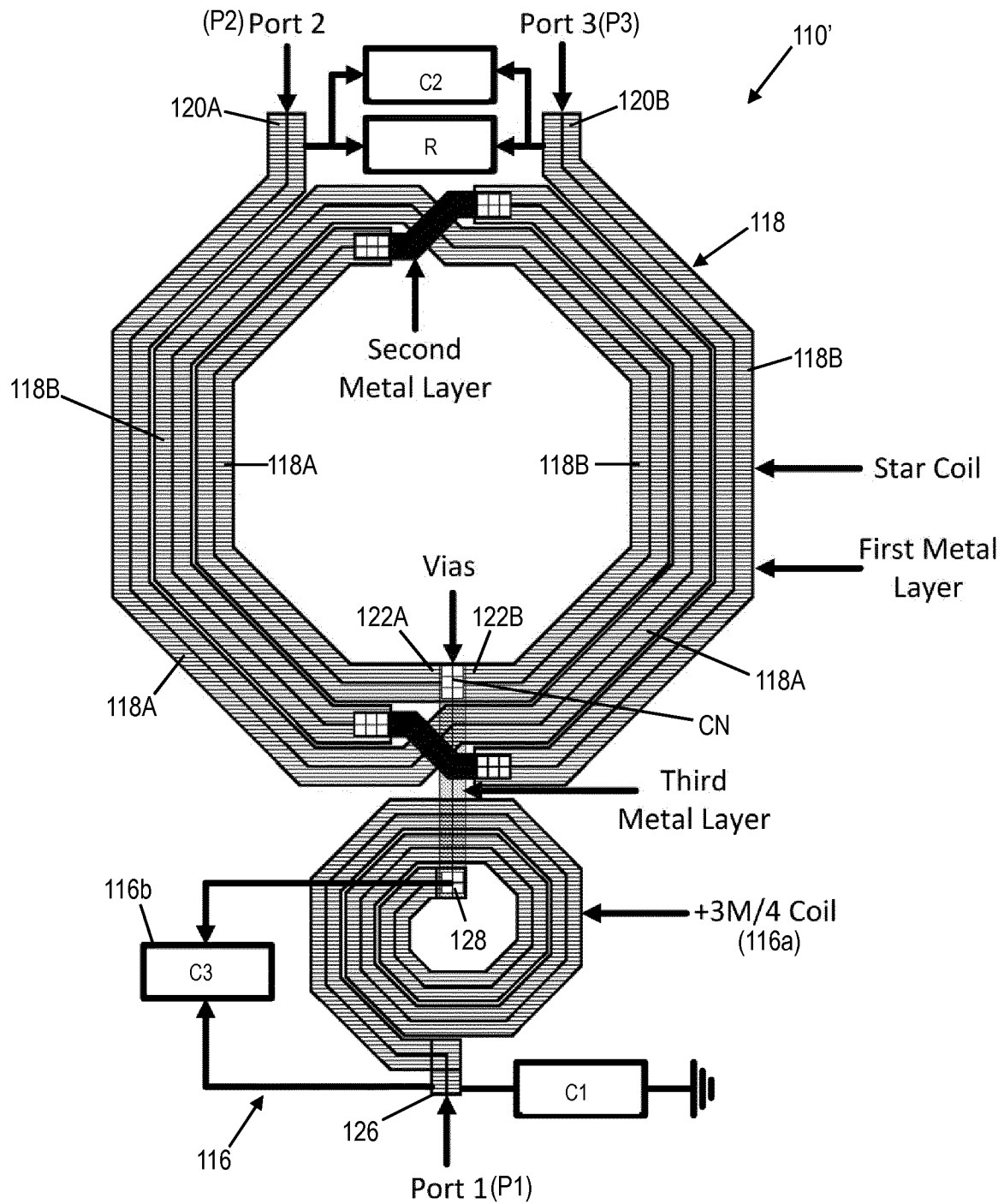
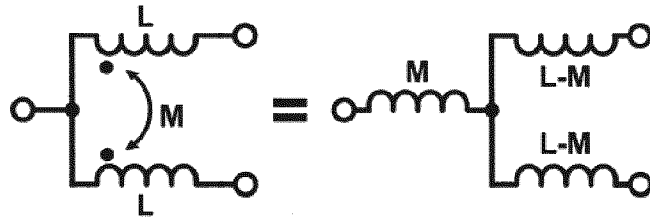
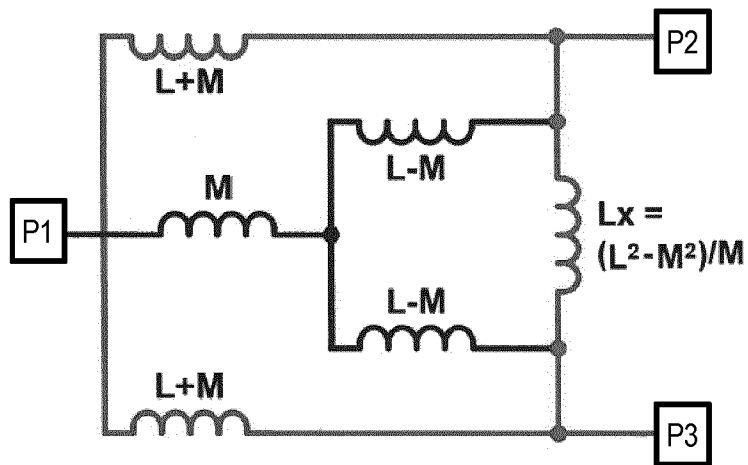


Fig. 7

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Fig. 8Fig. 9

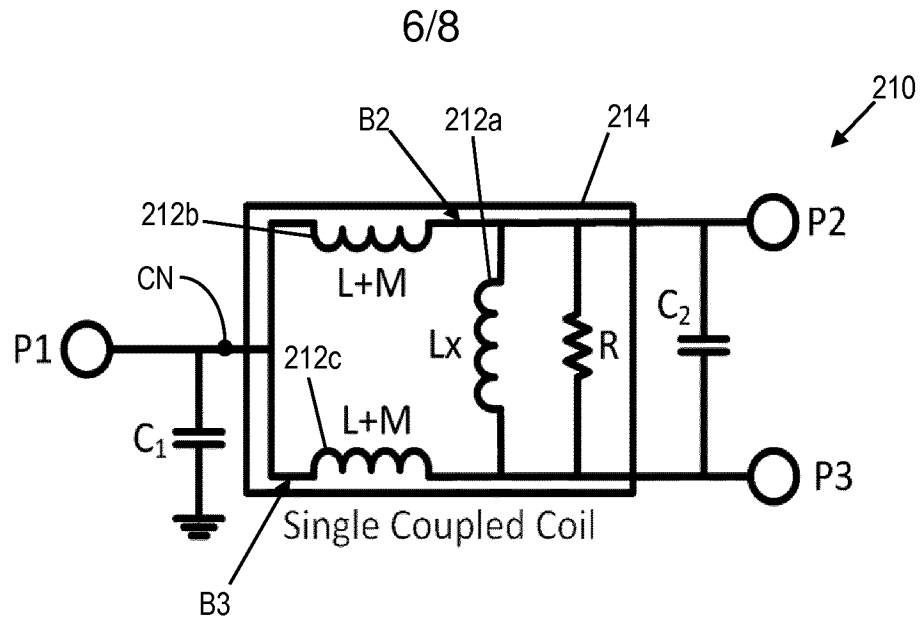


Fig. 10

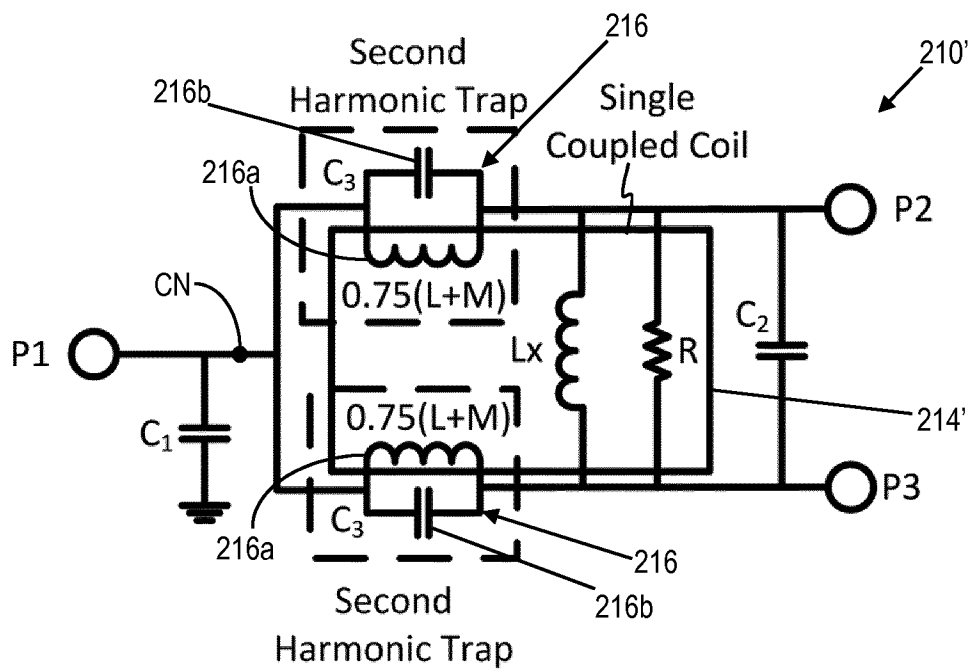


Fig. 11

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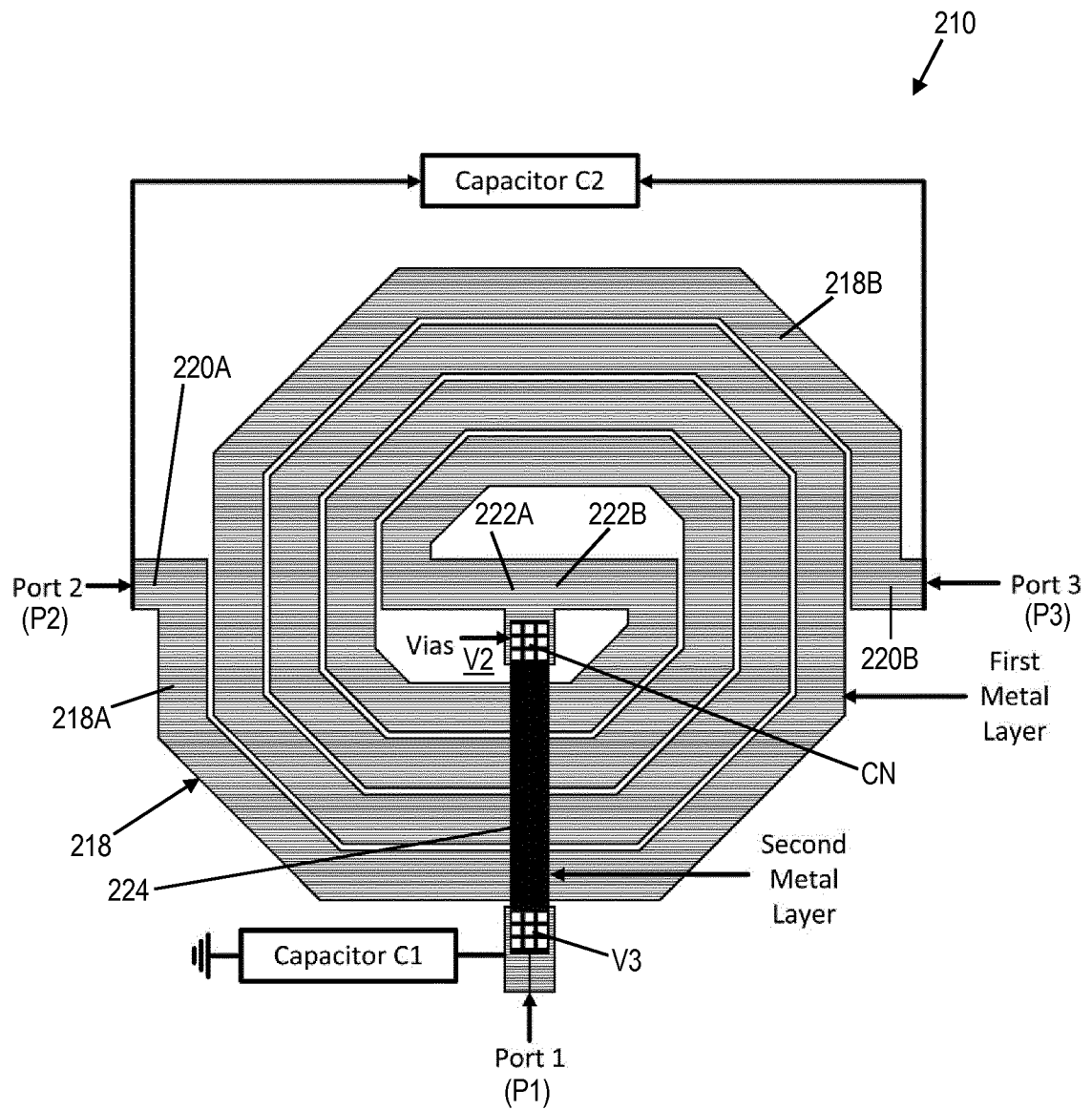


Fig. 12

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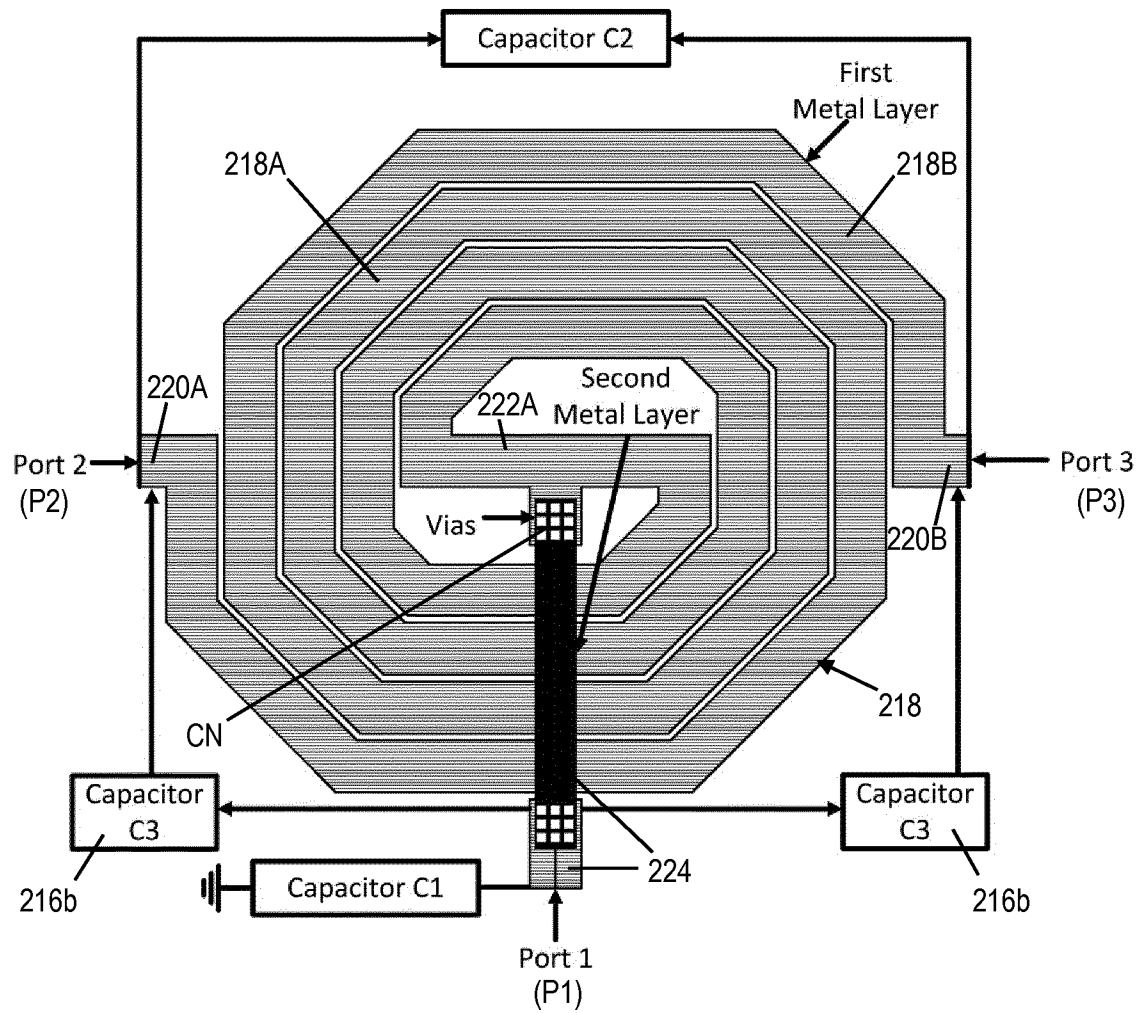


Fig. 13

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/073980

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01P5/16 H03H7/48
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01P H03H

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

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

EPO-Internal, WPI Data

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X	US 2018/248528 A1 (KIM KI JIN [KR] ET AL) 30 August 2018 (2018-08-30) figure 5 paragraph [0040] - paragraph [0051] -----	1,7-9
X	US 5 424 695 A (KONISHI YOSHIHIRO [JP]) 13 June 1995 (1995-06-13) figure 11 column 9, line 6 - line 34 ----- -/--	1,2,15, 24



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

25 November 2019

Date of mailing of the international search report

29/11/2019

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
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Authorized officer

Kalialakis, Christos

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/073980

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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X	FEI WANG ET AL: "An N-way transformer based Wilkinson power divider in CMOS", 2016 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM (IMS), IEEE, 22 May 2016 (2016-05-22), pages 1-4, XP032941316, DOI: 10.1109/MWSYM.2016.7540292 [retrieved on 2016-08-10] figure 1 figure 2 figure 7 Section II, first paragraph Section II, penultimate paragraph -----	1,3-5,12-14,16-23,26

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Information on patent family members

International application No

PCT/EP2019/073980

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