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(54) An integrated circuit based transformer

(57) An integrated circuit based transformer comprising a first layer of electrically conductive material and a second layer of electrically conductive material. The transformer comprises a primary winding having a first and a second portion (713, 711), wherein the first portion (713) of the primary winding is formed in the first layer of electrically conductive material and the second portion (711) of the primary winding is formed in the second layer of electrically conductive material; and a secondary winding having a first and a second portion (712, 714), wherein the first portion (712) of the secondary winding is formed in the second layer of electrically conductive material, and the second portion (714) of the secondary winding is formed in the first layer of electrically conductive material.

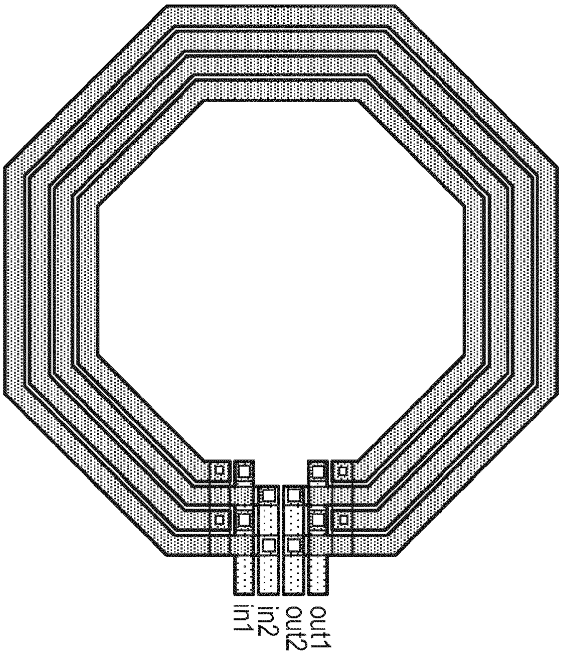

FIG. 22

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Description

[0001] The present disclosure relates to the field of integrated circuit based transformers and in particular, although not necessarily, integrated circuit based transformers that can be used in oscillator circuits

[0002] Transformers can be considered as a replacement for inductors in LC (inductor-capacitor) oscillator circuits in an attempt to reduce phase noise. This approach takes advantage of the mutual inductance between the primary and secondary windings of a transformer to increase the quality factor of the circuit. Although transformer-based LC oscillator circuits can have some degree of success in reducing phase noise, the presence of the secondary winding can degrade the performance of the transformer.

[0003] The listing or discussion of a prior-published document or any background in this specification should not necessarily be taken as an acknowledgement that the document or background is part of the state of the art or is common general knowledge. One or more aspects/embodiments of the present disclosure may or may not address one or more of the background issues.

[0004] According to a first aspect of the invention, there is provided an integrated circuit based transformer comprising:

a first layer of electrically conductive material;
a second layer of electrically conductive material;
a primary winding having a first and a second portion, wherein the first portion of the primary winding is formed in the first layer of electrically conductive material and the second portion of the primary winding is formed in the second layer of electrically conductive material, and
a secondary winding having a first and a second portion, wherein the first portion of the secondary winding is formed in the second layer of electrically conductive material, and the second portion of the secondary winding is formed in the first layer of electrically conductive material.

[0005] By forming one portion of each winding in the first layer and one portion of each winding in the second layer, the average distance of each winding from a substrate on which the transformer can be situated can be made equal or nearly equal. In this way, the parasitic capacitance associated with the primary winding can be made equal or nearly equal to that of the secondary winding and the quality factor of the transformer can thereby be improved.

[0006] In addition, this transformer configuration can enable the total lengths of the primary and secondary windings to be made equal, or nearly equal. Improved performance and improved quality factor can be achieved when the primary and secondary windings are electrically identical or nearly identical to each other. Using primary and secondary windings that are of similar length therefore can help to increase the quality factor of the transformer.

[0007] Also, the overall footprint of the transformer can be reduced by forming one portion of each winding in the first layer of electrically conductive material and one portion of each winding in the second layer of electrically conductive material, rather than forming the first and second portions of each winding in the same layer. This provides a greater area on the substrate for other components and can assist with device miniaturisation.

[0008] The first portion of the primary winding may partly or completely overlie the first portion of the secondary winding. The second portion of the secondary winding may partly or completely overlie the second portion of the primary winding. This can further reduce the footprint of the transformer and can also improve the quality factor of the transformer. The quality factor of a transformer is also dependent upon the degree of magnetic coupling (represented by the coupling coefficient) between the primary and secondary windings. By superimposing at least part of the primary winding onto at least part of the secondary winding, magnetic coupling between the windings can occur from both the edges and surfaces of the windings. This can further improve the quality factor and performance of the transformer.

[0009] The transformer may comprise a substrate. The first and second layers of electrically conductive material may be located on the same side of the substrate. The first layer of electrically conductive material may be an upper layer as it can be furthest from the substrate when the transformer is horizontal with the substrate below the metal layers. Similarly the second layer of electrically conductive material may be a lower layer as it can be closer to the substrate than the first layer of electrically conductive material.

[0010] The upper layer of electrically conductive material may have a greater thickness than the lower layer of electrically conductive material and therefore may have a lower resistance. In such an embodiment, the total resistance of the primary winding can be made equal or nearly equal to the resistance of the secondary winding because one portion of each winding is formed in the upper layer and one portion of each winding is formed in the lower layer.

[0011] The first portion of the secondary winding and/or the second portion of the primary winding may have a greater width than the first portion of the primary winding and/or the second portion of the secondary winding, respectively. In examples where the thickness of the lower layer of electrically conductive material is smaller than the thickness of the upper layer of electrically conductive material, increasing the width of the portions of the windings that are in the lower layer causes the electrical resistance of the lower layer to be decreased, thereby compensating for the reduced thickness and improving the quality factor of the transformer by making the electrical properties of the two layers of electrically conductive material more similar.

[0012] Each portion of the primary and secondary winding may be a plurality of turns, one turn, half a turn, or any other fraction of a turn, of the respective winding. Alternatively, each portion of the primary and secondary winding may be part of a turn of the respective winding. Each portion/turn may have a square, circular or N-sided polygonal shape (for example octagonal) in plan view.

[0013] The first portion of the primary winding may be concentric with the second portion of the secondary winding. The first portion of the secondary winding may be concentric with the second portion of the primary winding.

[0014] The first portion of the primary winding may be electrically connected to the second portion of the primary winding by a vertical connector. The first portion of the secondary winding may be electrically connected to the second portion of the primary secondary by a vertical connector. One or more of the vertical connectors may be a via. It will be appreciated that the term "vertical" should be construed as transverse to the plane of the layers of electrically conductive material.

[0015] The use of vertical connectors to connect the portions of the windings can help to reduce the footprint of the transformer. Electrical connections such as traces and bond wires may not need to be located adjacent to the transformer windings as the vertical connectors can provide the necessary connections. Furthermore, vertical connectors can be shorter than would be the case with bond wires, for example, which can be particularly advantageous at GHz frequencies where electrical connections can act as unwanted inductors and/or resistors in series with the transformer windings. The use of relatively short vertical connectors can help to reduce the magnitude of the inductance or resistance provided by the connectors and therefore improve the performance of the transformer.

[0016] The vertical connector used to electrically connect the first portion of one winding to the second portion of the same winding may pass through a hole formed in the other winding. Passing the vertical connector through a hole in the other winding helps to reduce the length of this electrical connection, thereby reducing the associated inductance/ resistance of the connector. The use of a hole also enables the perimeter of the footprints of the primary and secondary windings to be made identical, which can improve the quality factor of the transformer.

[0017] The integrated circuit based transformer may comprise a bridging connector in a third layer of electrically conductive material. The third layer of layer of electrically conductive material may be located between the second layer of electrically conductive material and the substrate. That is, the third layer may be lower than the second layer of electrically conductive material. A vertical connector which passes through the hole formed in the other winding may form an electrical connection between a portion of a winding in the upper layer and the bridging connector. The bridging connector may also be electrically coupled to a portion of a winding in a lower layer by a vertical connector. In this way, an electrical connection between portions of windings in different layers can be provided.

[0018] The primary and secondary windings may each comprise first and second terminals configured to enable a flow of electrical current into and out of each winding. The first and second terminals may be referred to as input and output terminals respectively. The first and second terminals of the primary winding may be formed from the same layer of electrically conductive material as the first and second terminals of the secondary winding. Forming the first and second terminals of each winding in the same layer facilitates convenient fabrication of the terminals. The first and second terminals of each winding may be formed from the upper layer of electrically conductive material. In examples where the upper layer of electrically conductive material is thicker than the lower layer of electrically conductive material, forming the first and second terminals of each winding in the upper layer can help to reduce the electrical resistance associated with the first and second terminals.

[0019] The integrated circuit based transformer may comprise a primary centre tap electrically connected to the primary winding and/or a secondary centre tap electrically connected to the secondary winding. The primary centre tap and the secondary centre tap may be provided in the same layer or separate layers of electrically conductive material, which may be the same layer as the bridging connector. If the primary or secondary centre taps are held at zero volts, the transformer may be used to process a differential signal instead of a single-ended signal. The primary and secondary centre taps may be electrically connected to their respective windings by one or more vertical connectors.

[0020] One centre tap may be electrically connected to the first portion of its respective winding by a first vertical centre tap connector and to the second portion of its respective winding by a second vertical centre tap connector. The first and second centre tap connectors may be connected to a midpoint of a turn of that winding. The other centre tap may be electrically connected to the first portion of its respective winding by third and fourth vertical centre tap connectors and to the second portion of its respective winding by fifth and sixth vertical centre tap connectors. The third and fourth centre tap connectors may be equally spaced either side of a midpoint of a turn of the winding. Similarly, the fifth and sixth centre tap connectors may be equally spaced either side of a midpoint of a turn of the winding. This configuration enables each winding of the transformer to be tapped at the effective midpoint of its length.

[0021] One or more of the vertical centre tap connectors may be a via. At least one of the vertical connectors used to electrically connect a centre tap to its respective winding may pass through a hole formed in the other winding. This enables the centre taps for the primary winding and the secondary winding to be provided in the same layer of electrically conductive material.

[0022] One of the centre taps may have a linear configuration comprising an elongate element. The other centre tap may have a forked configuration comprising first and second prongs. The centre taps may be electrically connected to their respective windings such that the first and second prongs of the forked centre tap are positioned symmetrically on either side of the elongate element of the linear centre tap. This configuration enables each winding of the transformer to be tapped at the effective midpoint of its length, even when the primary and secondary centre taps are formed from the same layer of electrically conductive material.

[0023] The primary and secondary windings may each have third and fourth portions. The third portion of the primary winding and the fourth portion of the secondary winding may be formed in the first layer of electrically conductive material. The third portion of the secondary winding and the fourth portion of the primary winding may be formed in the second layer of electrically conductive material. The transformer may be configured such that the third portion of the primary winding overlies the third portion of the secondary winding and the fourth portion of the secondary winding overlies the fourth portion of the primary winding. Increasing the number of portions in each winding can cause an increase in the inductance of the respective windings. This results in a greater degree of magnetic coupling between the primary and secondary windings, and therefore an increase in the quality factor of the inductor, although this may be at the expense a larger transformer footprint.

[0024] The numbering of the winding portions (first, second, third and fourth) may or may not correspond with the order in which electrical current travels through each winding.

[0025] According to a further aspect of the invention, there is provided an oscillator circuit comprising at any integrated circuit based transformer described herein.

[0026] A description is now given, by way of example only, with reference to the accompanying drawings, in which:-

figure 1 illustrates schematically an LC oscillator circuit;
figure 2 illustrates schematically the phase noise associated with the output signal of an LC oscillator circuit;
figure 3 illustrates schematically a transformer-based LC oscillator circuit;
figure 4 illustrates the impedance magnitude, impedance phase, and quality factor for a transformer-based LC tank;
figure 5 illustrates graphically the variation in quality factor with coupling coefficient for a transformer-based LC oscillator circuit;
figure 6 illustrates graphically the variation in quality factor with winding resistance for a transformer-based LC oscillator circuit;
figure 7a illustrates schematically the bottom layer of a two-turn transformer according to an embodiment of the invention;
figure 7b illustrates schematically the top layer of the transformer of figure 7a;
figure 7c illustrates a cross-section view of the transformer of figure 7a;
figure 8a illustrates schematically the bottom layer connections of the two-turn transformer shown in figure 7a;
figure 8b illustrates schematically the top layer connections of the two-turn transformer shown in figure 7b;
figures 9a and 9b illustrate schematically a two-turn transformer according to another embodiment of the invention;
figures 10a to 10c illustrate schematically a two-turn transformer according to an embodiment of the invention that has primary and secondary centre taps;
figures 10d and 10e illustrate an octagonal two-turn transformer according to an embodiment of the invention;
figures 11a to 11c illustrate schematically a four-turn transformer according to an embodiment of the invention;
figure 12a illustrates schematically the bottom layer connections of the four-turn transformer shown in figures 11a to 11c;
figure 12b illustrates schematically the top layer connections of the four-turn transformer shown in figures 11a to 11c;
figure 13 illustrates graphically the theoretical variation in coupling coefficient with frequency for a transformer according to an embodiment of the invention;
figure 14 illustrates graphically experimental results that illustrate the variation in coupling coefficient with frequency for a transformer according to an embodiment of the invention;
figure 15 illustrates graphically the theoretical variation in self, mutual and effective inductance with frequency for a transformer according to an embodiment of the invention;
figure 16 illustrates graphically experimental results that illustrate the variation in self, mutual and effective inductance with frequency for a transformer according to an embodiment of the invention;
figure 17 illustrates graphically the theoretical variation in winding resistance with frequency for a transformer according to an embodiment of the invention;
figure 18 illustrates graphically experimental results that illustrate the variation in winding resistance with frequency for a transformer according to an embodiment of the invention;
figure 19 illustrates graphically the theoretical variation in maximum available gain with frequency for a transformer according to an embodiment of the invention;
figure 20 illustrates graphically experimental results that illustrate the variation in maximum available gain with

frequency for a transformer according to an embodiment of the invention;

figure 21 illustrates graphically the variation in relative quality factor for different coil configurations including an embodiment of the invention;

figure 22 illustrates an octagonal layout topology of a transformer according to an embodiment of the invention;

figures 23a - 23h illustrate a synoptic construction of a multi-path transformer according to an embodiment of the invention; and

figure 24 illustrates a layout topology of a circular transformer according to an embodiment of the invention.

[0027] Embodiments of the present invention relate to an integrated circuit based transformer having a first layer of electrically conductive material and a second layer of electrically conductive material. Such a transformer may also be referred to as a monolithic transformer. The transformer has a primary winding and a secondary winding. Each of the primary winding and secondary winding are split between the first and second layers of electrically conductive material. Providing the windings in this way can enable the electrical properties of the two windings to be similar to each other, which enables a high coupling coefficient to be achieved. This in turn allows a transformer with a high quality factor to be provided.

[0028] In high frequency and performance applications (such as those operating in the Ku, K, Ka and W band and THz applications) circuit designs will often involve a combination of analogue and microwave design techniques and often incorporate transmission lines, splitters, couplers and transformers. Typically, integration of local oscillators into these circuits will present new challenges as only a limited tuning range may be achievable in practical implementations and there can be strict requirements in terms of phase noise performance that are imposed by communication standards.

[0029] The increasing need for reliable wireless communications has led to a demand for more efficient systems operating at ever higher frequencies. As a result of the limited number of bands available at radio frequencies (RF), however, it is important that a number of different channels are able to operate within a given frequency band with minimal interference. Known wireless systems are plagued with interference and signal degradation as a result of phase noise.

[0030] Figure 1 shows a theoretical LC oscillator which is commonly used in RF systems and generates the periodic signal using an inductor L 103 and capacitor C 104. LC oscillators are a popular choice for RF systems because they tend to exhibit lower phase noise than other oscillator circuits. This is primarily a result of the small number of electrical components required.

[0031] Figure 2 illustrates schematically the phase noise associated with the output signal of an LC oscillator circuit. Phase noise is a random variation in the frequency of the output signal of the system. The frequency spectrum of an ideal system comprises a single spike 201 at the carrier frequency (f_o). Figure 2 also shows that the spectrum of a practical system has "skirts" 202 around the carrier frequency f_o indicating that the output signal contains significant energy at frequencies other than the carrier frequency. The unwanted frequencies can interfere with the signals of other RF systems operating within the same band. The interference can significantly degrade the signal-to-noise ratio of these systems thereby reducing the signal integrity. This effect is seen in both the transmitter and receiver circuitry of RF systems. As a result, the Federal Communications Commission (FCC) has laid down guidelines for the output of wireless communication systems which, amongst other things, limit the magnitude of phase noise which is acceptable at a particular offset from the carrier frequency.

[0032] Many RF systems comprise an oscillator circuit which is used to generate the periodic output signal. Oscillators are often the dominant source of phase noise and signal degradation in RF systems.

[0033] Despite the low phase noise associated with standard LC oscillator circuits, they may not be capable of complying with current requirements and standards. A number of models have been developed which allow circuit designers to estimate the phase noise introduced by the oscillator. One such model is the linear time invariant model proposed by D. B. Leeson in 1966. This is an equation that can be used to calculate the phase noise (PN) at a given offset frequency (Δf) from the centre frequency (f_0),

$$PN(\Delta f) = 10\log\left[\frac{2FkT}{P_s}\left\{1+\left(\frac{f_o}{2Q\Delta f}\right)^2\right\}\left(1+\frac{f_c}{|\Delta f|}\right)\right]$$

where F is the noise factor of the oscillator; k is Boltzmann's constant; T is the absolute temperature; P_s is the output power of the oscillator; Q is the quality factor of the oscillator; and f_c is the $1/f$ corner frequency.

[0034] This model shows that the phase noise of an oscillator may be reduced by increasing the oscillator amplitude and/or increasing the quality factor of the oscillator. Increasing the output power requires an increase in the biasing current or tank inductance of the circuit. Increasing the biasing current can increase power consumption whilst increasing the inductance can cause a decrease in the tuning range of the circuit. Therefore, there exists a trade-off between low phase noise, high tuning range and power consumption. In order to help reduce the degradation in performance of the oscillator, LC tanks that include a transformer instead of a single coil inductor can be used. Use of such a transformer can improve performance by increasing the quality factor of the LC tank by increasing the ratio of inductance (self inductance (L) and mutual inductance (M)) to the associated losses.

[0035] Electrical parameters of a transformer-based resonator that are of interest to a circuit designer include the transformer turns ratio n and the coefficient of magnetic coupling k. A high magnetic coupling value reduces losses and therefore improves the quality factor. If the magnetic coupling between windings is perfect (that is, there is no leakage of the magnetic flux), then k is unity. In contrast, k is zero for completely uncoupled coils. A practical transformer will have a k-factor between these two extremes. Typically for an on-chip monolithic transformer a k-factor between 0.70 and 0.85 can be achieved. Figure 3 shows a schematic drawing of a transformer based resonator; that is an LC resonator in which the inductor has been replaced with a transformer 305. The circuit has two resistors, r_1 306 and r_2 303, and two capacitors C_1 304 and C_2 308. In this circuit, the self-inductance of the primary winding 306 is L_1 and the self-inductance of the secondary winding 307 is L_2. The mutual inductance of the windings 306, 307 is M.

[0036] The input resonator impedance Z_{in}^{Transf} 309 of the resonator of Figure 3 is given by:

$$Z_{in}^{transf} = \frac{(M^2 - L_1L_2)\omega^2 + \frac{L_1}{C_2} + r_1r_2 + j\left(L_1r_2\omega + L_2r_1\omega - \frac{r_1}{C_2\omega}\right)}{r_2 - C_1\omega\left(L_1r_2\omega + L_2r_1\omega - \frac{r_1}{C_2\omega}\right) + j\left[C_1\omega\left((M^2 - L_1L_2)\omega^2 + \frac{L_1}{C_2} + r_1r_2\right) + L_2\omega - \frac{1}{C_2\omega}\right]}$$

[0037] This impedance can also be written using the following general form:

$$Z_{in}^{transf} = R + jX$$

[0038] In which R is the real part of the impedance and X the imaginary part, which is also known as susceptance.

[0039] From these equations it will be understood that the quality factor at its resonant frequency ω_0 can be expressed as:

$$Q = \frac{\omega_0}{2R} \cdot \frac{dX}{d\omega}$$

[0040] Figure 4 illustrates graphically: (i) the magnitude of Z_{in} 402; (ii) the phase of Z_{in} 406; and (iii) the computed quality factor 410 for a 10GHz LC resonator versus frequency.

[0041] The transformer in the transformer-based resonator behaves like a single coil having a self-inductance value equal to the sum of the self inductance of a coil of the transformer (L) and the mutual inductance between the coils (M). The quality factor of the transformer based resonator is:

$$Q = (1+k) \times Q_{eff}$$

where Q_{eff} is the quality factor of a single coil with L for self-inductance value, and k is the magnetic coupling factor between the windings.

[0042] Therefore, it will be appreciated that the higher the value for the magnetic coupling factor (k), the higher the quality factor (*Q*). However, the higher the value for the magnetic coupling factor (*k*) the higher the coupling capacitance and thus the lower the self-resonant frequency, which can limit the usability of the device.

[0043] Figure 5 shows the relationship between coupling coefficient (k) and quality factor for a transformer based resonator along with the quality factor of a single coil (denoted by reference numeral 508). It can be seen that the quality factor increases with an increasing coupling coefficient.

[0044] To increase the coupling coefficient between the windings of the transformer, and thereby increase the quality factor, the primary and secondary windings of the transformer should be made electrically similar to each other. For example, the windings should have the same or similar length, width, thickness and be made of the same material. Locating the windings in close proximity to one another can also increase the coupling coefficient.

[0045] Figure 6 illustrates graphically the relationship between quality factor of the resonator and serial resistance of the secondary coil in a transformer-based resonator. The serial resistance of the primary coil is set as a constant value. It can be seen that the quality factor decreases as the resistance of the secondary winding increases.

[0046] Another parameter which affects the quality factor of a transformer is the distance between each winding and an underlying substrate. The greater the distance of each winding from the substrate, the smaller the effects of parasitic capacitance on the operation and frequency response of the transformer.

[0047] Figures 7a, 7b, 7c, 8a and 8b illustrate parts or views of an integrated circuit based transformer according to an embodiment of the invention. The transformer in this example has a primary and a secondary winding, which each comprise two square-shaped turns. One turn of each winding is provided in a first layer of electrically conductive material as shown in Figure 7b. The other turn of each winding is provided in a second layer of electrically conductive material as shown in Figure 7a. The windings in the first and second layers are joined together by vias as shown in Figures 8a and 8b and/or by a bridging connector 721 shown in Figure 7a. The bridging connector is in a bridging layer, which is a different layer to the first and second layers.

[0048] The integrated circuit based transformer of Figures 7 and 8 may be implemented on a substrate, with the first and second layers of electrically conductive material located on the same side of the substrate. The first layer of electrically conductive material may be an upper layer as it can be furthest from the substrate when the transformer is horizontal with the substrate below the metal layers. Similarly the second layer of electrically conductive material may be a lower layer as it can be closer to the substrate than the first layer of electrically conductive material.

[0049] Figure 7a shows a plan view of turns 711, 712 in the lower layer of the transformer. The two turns 711, 712 are located one inside the other. The inner turn 711 is the second turn of the primary winding. The outer turn 712 is the first turn 712 of the secondary winding. In this example, the turns 711, 712 are concentric.

[0050] Also shown in Figure 7a in dotted lines are two bridging connectors 721 in a bridging layer, which is separate from and underneath the lower layer. The bridging connectors 721 are described below in more detail.

[0051] Figure 7b shows a plan view of turns in the upper layer of the transformer. The two turns 713, 714 are located one inside the other. The inner turn 714 is the second turn of the secondary winding. The outer turn 713 is the first turn of the primary winding. Once again, the turns 713, 714 are concentric.

[0052] The upper layer also comprises a first terminal 709 and a second terminal 715 for the primary winding. The terminals 709, 715 are configured to enable a flow of electrical current into and out of the primary winding. The upper layer also comprises a first terminal 710 and a second terminal 716 configured to enable a flow of electrical current into and out of the secondary winding. Forming the first 709, 710 and second 715, 716 terminals of each winding in the same layer facilitates convenient fabrication of the terminals and convenient connection to other components. Furthermore, in examples where the upper layer of electrically conductive material is thicker than the lower layer of electrically conductive material, forming the first 709, 710 and second 715, 716 terminals of each winding in the upper layer can help to reduce the electrical resistance associated with the first 709, 710 and second 715, 716 terminals and therefore improve the electrical properties of the transformer.

[0053] Figure 7c shows a cross-section through the upper and lower layers of the transformer along the line c-c shown in figures 7a and 7b. As can be seen, the transformer is configured such that the first turn 713 of the primary winding overlies the first turn 712 of the secondary winding and the second turn 714 of the secondary winding overlies the second turn 711 of the primary winding. The diagonal links between turns that are shown in figure 7c as dotted lines are illustrative of the links between the layers that are provided by vertical connectors and/or bridging connectors.

[0054] Figures 8a and 8b show further details of the boxed regions 717, 718 shown in figures 7a and 7b respectively and are used to describe the connections between the turns in the upper and lower layers. The upper and lower electrically conductive layers are electrically connected together by vertical connectors such as contact pads and/or vias.

[0055] In relation to the primary winding, it can be seen from figure 8b that the first 809 and second 815 terminals of the primary winding are formed as extensions of the first turn 813 in the upper layer and serve as connectors between the first 813 and second 811 turns of the primary winding. There is direct connection between the first and second terminals 809, 815 and the first turn 813 of the primary winding as they are in the same layer. Vertical connectors 819 are provided between the lower surface of the first 809 and second 815 terminals of the primary winding in the upper layer and the upper surface of the second turn 811 of the primary winding in the lower layer. The vertical connectors

819 may be provided as vias to put the first and second turns of the primary winding in direct contact with each other. In this example, first and second terminals 809, 815 extend from an external connection region 809a, 815a near the periphery of the transformer to a vertical connection region 809b, 815b where the vertical connectors 819 are provided. The vertical connection regions of the terminals are above the ends of the second turn 811 of the primary winding in the lower layer.

[0056] Considering now the secondary winding, the first 810 and second 816 terminals are connected to the first and second turns of the secondary winding through a number of vertical connectors. The first 810 and second 816 terminals in this example can be considered as islands of electrically conductive material in the upper layer inasmuch as they are not provided as direct extensions of the second turn 814 in the upper layer.

[0057] Vertical connectors 820 are provided between the lower surface of the first 810 and second 816 terminals of the secondary winding in the upper layer (shown in figure 8b) and the upper surface of the first turn 812 of the secondary winding in the lower layer (shown in figure 8a) to connect the first 810 and second 816 terminals of the secondary winding to the first turn 812 of the secondary winding in the lower layer.

[0058] In order to connect the first turn 812 of the secondary winding in the lower layer to the second turn 814 of the secondary winding in the upper layer in parallel, additional bridging connectors 821 and vias 823 are used in this example. As indicated above, the bridging connectors 821 are located in a layer of electrically conductive material that is below the lower layer. The bridging connectors 821 span the first, outer, turn 812 of the secondary winding in the lower layer and the second, inner, turn 814 of the secondary winding in the upper layer. As shown in figure 8a, vertical connectors 822 are provided between the lower surface of the first turn 812 and the upper surface of the bridging connectors 821 to create an electrical connection between the first turn 812 of the secondary winding in the lower layer and the bridging connectors 821. Also, vertical connectors 823 are provided between the lower surface of the second turn 814 in the upper layer and the upper surface of the bridging connectors 821 in the bridging layer through holes 824 in the second turn 811 of the primary winding in the lower layer. That is, the electrical connection between the bridging layer and the upper layer passes through, but does not make electrical contact with, the intermediate lower layer of electrically conductive material in which the second turn 811 of the primary winding in the lower layer is located. In this way, the connection does not need to be provided outside of the perimeter of the turns, and good electrical similarity of the windings can be maintained.

[0059] The use of vertical connectors helps to minimise the footprint of the transformer. This is because the electrical connections are formed directly between the transformer windings, thereby negating the need to form electrical connections such as traces or bond wires that are adjacent to the transformer windings. Furthermore, particularly at GHz frequencies, electrical connections can act as unwanted inductors and/or resistors in series with the transformer windings. The use of vertical connectors therefore helps to minimise the length of these electrical connections and therefore the magnitude of unwanted inductance or resistance, and may also minimise any differences in length that might otherwise occur with other types of connection thereby ensuring greater electrical similarity between the primary and secondary windings. Passing vertical connectors 823 through holes 824 in the second turn 811 of the primary winding also helps to minimise the length of these connectors along with the associated inductance/resistance.

[0060] The configuration of Figures 7 and 8 can provide a number of advantages. These can include a reduction in the overall footprint of the transformer, that is the substrate area occupied by the transformer, as one turn 713, 714 of each winding is formed in the upper layer of electrically conductive material and one turn 711, 712 of each winding in the lower layer of electrically conductive material (rather than forming the first 712, 713 and second 711, 714 turns of each winding in the same layer). This provides a greater area on the substrate for other components and facilitates device miniaturisation.

[0061] Also, the transformer configuration enables the total lengths of the primary and secondary windings to be made equal or nearly equal. As discussed above, the coupling coefficient, and therefore the quality factor of the transformer, is improved when the primary and secondary windings are electrically identical or similar. Using equal lengths for each winding therefore helps to increase the quality factor of the transformer. Also, by superimposing a turn 713 of the primary winding onto a turn 712 of the secondary winding (and vice versa), magnetic coupling can occur from both the edges and surfaces of the windings. This acts to further increase the coupling coefficient and quality factor of the transformer.

[0062] In addition, by forming one turn 713, 714 of each winding in the upper layer and one turn 711, 712 of each winding in the lower layer, the average distance of each winding from the substrate, and therefore the parasitic capacitance associated with each winding, is also equal or nearly equal. Since improved performance can be achieved when the primary and secondary windings are electrically identical, equality in the electrical resistance and parasitic capacitance of the windings can increase the quality factor of the transformer further still.

[0063] As discussed above, one advantage of the present transformer configuration is that each winding comprises a portion in the upper layer of electrically conductive material and a portion in the lower layer of electrically conductive material. In this example each portion is a complete turn, although this need not necessarily be the case.

[0064] In some known IC implementations, the lower layer of electrically conductive material can be thinner than the upper layer of electrically conductive material. Therefore, the electrical resistance of the lower layer of electrically conductive material is likely to be greater than that of the upper layer. In accordance with the graph of figure 6, this can lower the quality factor of the transformer.

[0065] In examples where the upper layer of electrically conductive material has a greater thickness than the lower layer of electrically conductive material, the total resistance of the primary winding can be close to the total resistance of the secondary winding because one turn 713, 714 of each winding is formed in the upper layer and one turn 711, 712 of each winding is formed in the lower layer. The difference between the total resistances of the two windings may be as little as 5% across the wide frequency range. In most of the cases, this can represent a difference of less than 50 mΩ between primary and secondary windings at DC, which can compare favourably with the prior art.

[0066] Figures 9a and 9b illustrate a transformer according to an embodiment of the invention in which the upper layer of electrically conductive material is thicker than the lower layer. Features of figures 9a and 9b that are similar to the corresponding features of figures 7a and 7b will not necessarily be described again here. In this embodiment, the width of the turns 911, 912 in the lower layer is greater than the width of the turns 913, 914 in the upper layer in order to compensate for the reduced thickness of the lower layer. That is, the width of the turns in the different layers can be set such that the resistance of the respective turns is sufficiently similar or the same.

[0067] Figure 10a shows a top view of a transformer according to an embodiment of the invention including a primary centre tap 1025 and a secondary centre tap 1026. Figure 10b shows a close-up view of the centre taps 1025, 1026 from below along with the turns in the lower layer of the transformer. Figure 10c shows a close-up view of the centre taps 1025, 1026 from above along with the turns in the upper layer of the transformer.

[0068] Figures 10b and 10c are used to describe the vertical connections between the turns in the upper and lower layers and the centre taps 1025, 1026.

[0069] Features of figures 10a to 10c that are similar to the corresponding features of figures 7a and 7b will not necessarily be described again here.

[0070] The centre taps 1025, 1026 are provided in an electrically conductive layer that is a different layer to the upper and lower layers. The centre taps 1025, 1026 can be connected to external components in order to configure operation of the transformer.

[0071] The use of a primary and/or secondary centre tap allows the turns ratio, and therefore the gain of the transformer, to be varied. If the primary or secondary centre taps are held at zero volts, the transformer may be used to process differential signals instead of a single-ended signals.

[0072] In this example, the primary centre tap 1025 has a linear configuration comprising an elongate element 1027. The elongate element 1027 passes underneath both the inner turn and outer turn in both the upper and lower layers. The elongate element 1027 is in the vicinity of the midpoint of each turn. The primary centre tap 1025 is electrically connected to the first and second turns by vertical connectors that are similar to those used to connect the first and second turns of each winding. The primary centre tap 1025 is electrically connected to the first turn 1013 of the primary winding in the upper layer by a first vertical connector 1031 and to the second turn 1011 of the primary winding in the lower layer by a second vertical connector 1032. Since the first turn 1012 of the secondary winding is positioned between the primary centre tap 1025 and the first turn 1013 of the primary winding in the upper layer, the first vertical connector 1031 passes through a hole (not shown) in the first turn 1012 of the secondary winding in order to make the electrical connection. The hole can be similar to the hole illustrated in figure 8a.

[0073] The secondary centre tap 1026 in this example has a forked configuration comprising first 1028 and second 1029 prongs. The secondary centre tap 1026 is electrically connected to both turns of the secondary windings such that the first 1028 and second 1029 prongs of the secondary centre tap 1026 are positioned symmetrically on either side of the mid-point of the turns, and therefore either side of the elongate element 1027 of the primary centre tap 1025. This configuration enables each winding of the transformer to be tapped at the effective midpoint of its length, even when the primary 1025 and secondary 1026 centre taps are formed in the same layer of electrically conductive material.

[0074] The secondary centre tap 1026 is electrically connected to the first turn 1012 of the secondary winding in the lower layer by third 1033 and fourth 1034 vertical connectors and to the second turn 1014 of the secondary winding in the upper layer by fifth 1035 and sixth 1036 vertical connectors. Since the second turn 1011 of the primary winding is positioned between the secondary centre tap 1026 and the second turn 1014 of the secondary winding, the fifth 1035 and sixth 1036 vertical connectors pass through holes (not shown) in the second turn 1011 of the primary winding in order to make the electrical connection in the same way as the first vertical connector 1031 passes through a hole to connect the primary centre tap 1025 to the first turn of the primary winding in the upper layer.

[0075] Figure 10d illustrates an octagonal two-turn monolithic transformer comprising primary and secondary centre taps, which are similar to those illustrated in figure 10a. Figure 10e illustrates a backside view of the transformer of figure 10d showing further details of the primary and secondary centre taps.

[0076] It will be appreciated that the transformer described herein is not limited to the use of two turns per winding. If, however, the upper layer of electrically conductive material has a greater thickness than the lower layer of electrically conductive material, then it may be desirable to provide an even number of turns in each winding. If an odd number of turns are used, one winding may comprise a greater number of turns in the upper layer than the other winding, which can lead to a difference between the electrical resistance of the windings and therefore a reduced coupling coefficient k.

[0077] Increasing the number of portions in each winding can cause an increase in the inductance of the respective windings. This can result in a greater degree of magnetic coupling between the primary and secondary windings, and therefore an increase in the quality factor of the inductor (albeit potentially at the cost of a larger transformer footprint).

[0078] Figure 11a shows a plan view of the bottom layer of a four-turn transformer according to an embodiment of the invention. Figure 11b shows a plan view of the top layer of the same four-turn transformer according to an embodiment of the invention. In this example, the first and second turns of each winding are as described with respect to figures 7a and 7b. In figures 11a and 11b, however, the primary and secondary windings each also have third and fourth turns. The third turn 1140 of the primary winding and the fourth turn 1139 of the secondary winding are formed in the upper layer of electrically conductive material. The third turn 1138 of the secondary winding and the fourth turn 1137 of the primary winding are formed in the lower layer of electrically conductive material. A cross-section through the transformer windings is shown in figure 11c. The diagonal links between turns that are shown in figure 11c are illustrative of the links between the layers that are provided by vertical connectors and/or bridging connectors. As can be seen, the transformer is configured such that the third turn 1140 of the primary winding overlies the third turn 1138 of the secondary winding and the fourth turn 1139 of the secondary winding overlies the fourth turn 1137 of the primary winding.

[0079] The input 1209, 1210 and output 1215, 1216 terminals used to enable a flow of electrical current into and out of each winding, and the vertical connectors used to electrically connect the turns of each winding are shown in figures 12a and 12b. Other than the fact that the terminals and connectors have been adapted for use with four-turn windings instead of two-turn windings, these features are as described previously.

[0080] Figure 13 shows the theoretical relationship between: (i) coupling coefficient k between primary and secondary windings; and (ii) frequency in Hz, for a transformer according to an embodiment of the invention. The theoretical results were obtained by simulation. Figure 14 shows experimental results corresponding to the theoretical prediction in figure 13 that illustrate the relationship between the coupling coefficient k and frequency.

[0081] As can be seen in figures 13 and 14, the coupling coefficient k remains largely constant across all frequencies with a value of about 0.9 in the theoretical illustration of figure 13 and about 0.98 in the experimental results of figure 14. This indicates that strong magnetic coupling between the primary and secondary windings is achievable over a wide frequency range using an embodiment of the invention.

[0082] Figure 15 shows the theoretical relationship between inductance values and frequency for a transformer according to an embodiment of the invention. Figure 16 shows experimental results that illustrate the same relationships. Shown in figures 15 and 16 are:

the self-inductance 1541, 1641 of the primary winding;
the self-inductance 1542, 1642 of the secondary winding;
the mutual inductance 1543, 1643 of the primary and secondary windings; and
the effective inductance (L+M) 1544, 1644 of the transformer.

[0083] As can be seen, the mutual inductance 1543, 1643 is comparable with the self-inductance 1541, 1542, 1641, 1642 of each winding. This is indicative of the coupling coefficient k being about one (unity) since M=kL. As a consequence of the high coupling coefficient, the effective inductance of the transformer can be greater than is achievable in the prior art. This high k value enables the number of turns (and therefore the transformer footprint) to be reduced without significantly reducing the performance of the transformer when compared with prior art devices.

[0084] Figure 17 shows the theoretical relationship between the serial resistance of the primary and secondary windings and frequency for a transformer according to an embodiment of the invention. Figure 18 shows experimental results that illustrate the theoretical relationship of figure 17.

[0085] It can be seen from figures 17 and 18 that the resistance of the two windings are very similar to each other across the frequency range illustrated in figures 17 and 18. As discussed above, a good electrical similarity between the primary and secondary windings can provide a good quality factor of the transformer.

[0086] Figure 19 shows the theoretical relationship between the maximum available gain (G_{max}) of a transformer according to an embodiment of the invention and frequency. Figure 20 shows experimental results that illustrate the theoretical relationship of figure 19. The G_{max} of prior art transformers is typically between 0.8 and 0.85. As can be seen in figures 19 and 20, a transformer according to an embodiment of the invention is capable of exceeding these values over a wide frequency range; between 3 and 20GHz in the simulation of figure 19 and between 2GHz and 50GHz in the experiment results of figure 20. This frequency range of "high" gain values can be wider than is achievable with the prior art.

[0087] Figure 21 illustrates the relative quality factor of a transformer according to an embodiment of the present invention, a single coil inductor and other types of transformers operating at a frequency of 10GHz.

[0088] The quality factor of a single coil inductor is shown with a quality factor of 1. The results have been normalised to the quality factor of the single coil inductor. A Shibata-type transformer has a relative quality factor of about 0.72, a Frlan-type transformer has a relative quality factor of about 0.9 and a Finlay-type transformer has a relative quality factor of about 1.27. The relative quality factor 2102 of the transformer according to an embodiment of the present invention has a value of about 1.44. As can be seen, the transformer according to this embodiment of the invention clearly outperforms the other transformers that are shown.

[0089] Additional simulations of phase noise calculations for a voltage controlled oscillator (VCO) including a transformer according to an embodiment of the invention show that:

- for a low frequency band, the phase noise can be reduced by 2dB compared to state-of-the-art transformers at a 1 MHz offset. This reduction can be improved to 3.3dB with copper back-end-of-line (BEOL) components.
- for a high frequency band, the phase noise can be reduced by 2.6dB compared to state-of-the-art transformers at a 1 MHz offset. This reduction can be improved to 3.0dB with copper back-end-of-line (BEOL) components.

[0090] Figure 22 illustrates an octagonal layout topology of a multi-path transformer according to an embodiment of the invention. Figures 23a to 23h show a synoptic construction of the transformer of figure 22. Similarities will be apparent to the skilled person between figures 23a-23h and figures 7a-7c, 8a-8b, 9a-9b, 11a-11c and 12a-12b.

[0091] Figure 23a shows an overview of a bottom/lower (second) metal layer. Figure 23b shows a view of the hollow vertical connection, which may be used to connect an top/upper (first) metal layer to the secondary coil. The "hollows" here are similar to the the above-described "holes". Figure 23c shows a via between the first and second metal layers forming a direct connection from the primary winding and a hollow connection on the secondary winding. Figure 23d shows a top/upper (first) metal layer. Figure 23e shows an overview of the top/upper (first) metal layer for the whole transformer.

[0092] Figure 23f shows a backside view of the hollow connection with the vias on the bottom/lower (second) metal layer. Figure 23g shows a backside view of the bottom/lower (second) metal layer of the secondary winding connected to the top/upper (first) metal layer by bridging connections and hollow connections. The lines are straight in this example, which can help limit resistive losses. Figure 23h shows a backside view with the complete terminals.

[0093] One or more transformers according to an embodiment of the invention may only have one turn on the primary winding and one turn on the secondary winding. Various segments in either the first metal layer or the second metal may be sub paths of the turn. Adding one sub-path can allow a reduction in the electrical resistance together with the self-inductance value of the winding. The overall width of primary and secondary turns can be equal to the number of sub-paths multiplied by the width of each sub-path.

[0094] Figure 24 illustrates a layout topology of a circular transformer according to an embodiment of the invention.

[0095] Typically using the metal just below the top metal (which is the case in most IC processes), may produce an increase in the serial resistance of the secondary winding, leading to a decrease of the resonator quality factor. This is a typical case in either BiCMOS or CMOS processes where the top metal is the thicker one. Higher parasitic capacitances with the substrate may be present, since larger windings are required to decrease the resistance of the secondary coil in a lower (thinner) metal layer. Dissymmetry between primary and secondary windings can give different Q factors. Higher losses from the secondary winding may degrade the quality factor.

[0096] Embodiments of the invention can be better than a transformer with an interleaved windings. An interleaved architecture may have both primary and secondary coils in the same metal layer, but may have a lower k (i.e., lower Q) value than embodiments of the present invention due to the reduced coupling between windings and a dissymmetry between coils. Higher losses may also result due to different crossing connections between windings.

[0097] Advantages of the embodiments described herein include the combination of a symmetrical transformer having a high coupling coefficient between windings, with reduced parasitic capacitive coupling to the substrate and low losses, thereby overcoming some of the abovementioned issues. Such transformers are suitable for use in mm wave applications.

Claims

1. An integrated circuit based transformer comprising:

a first layer of electrically conductive material;

a second layer of electrically conductive material;

a primary winding having a first and a second portion (713, 711), wherein the first portion (713) of the primary winding is formed in the first layer of electrically conductive material and the second portion (711) of the primary winding is formed in the second layer of electrically conductive material; and

a secondary winding having a first and a second portion (712, 714), wherein the first portion (712) of the secondary winding is formed in the second layer of electrically conductive material, and the second portion (714) of the secondary winding is formed in the first layer of electrically conductive material.

2. The integrated circuit based transformer of claim 1, wherein:

the first portion (713) of the primary winding partly or completely overlies the first portion (712) of the secondary winding; and
the second portion (711) of the primary winding partly or completely overlies the second portion (714) of the secondary winding.

3. The integrated circuit based transformer of claim 1 or claim 2, wherein each portion (711, 712, 713, 714) of the primary and secondary winding is a half turn of the respective winding.

4. The integrated circuit based transformer of any preceding claim, wherein the first portion (713) of the primary winding is concentric with the second portion (714) of the secondary winding, and the first portion (712) of the secondary winding is concentric with the second portion (711) of the primary winding.

5. The integrated circuit based transformer of any preceding claim, wherein the first portion (712) of the secondary winding and the second portion (711) of the primary winding have a greater width than the first portion (713) of the primary winding and the second portion (714) of the secondary winding.

6. The integrated circuit based transformer of any preceding claim, wherein the first portion (712, 713) of each winding is electrically connected to the second portion (711, 714) of the same winding by a vertical connector (819, 822, 823).

7. The integrated circuit based transformer of claim 6, wherein the vertical connector (823) used to electrically connect the first portion (712) of one winding to the second portion (714) of the same winding passes through a hole (824) formed in the other winding.

8. The integrated circuit based transformer of claim 7, wherein the integrated circuit based transformer comprises a bridging connector (821) in a bridging layer, and wherein the vertical connector (823) which passes through the hole (824) formed in the other winding forms an electrical connection with the bridging connector (821) in order to electrically connect the first portion (712) to the second portion (714).

9. The integrated circuit based transformer of any preceding claim, wherein the primary and secondary windings each comprise first (709, 710) and second (715, 716) terminals configured to enable a flow of electrical current into and out of each winding, respectively, and wherein the first (709) and second (715) terminals of the primary winding are formed from the same layer of electrically conductive material as the first (710) and second (716) terminals of the secondary winding.

10. The integrated circuit based transformer of any preceding claim, wherein the integrated circuit based transformer comprises a primary centre tap (1025) electrically connected to the primary winding and/or a secondary centre tap (1026) electrically connected to the secondary winding.

11. The integrated circuit based transformer of claim 10, wherein the primary (1025) and secondary (1026) centre taps are electrically connected to their respective windings by one or more vertical connectors (1031-1036).

12. The integrated circuit based transformer of claim 10 or 11, wherein one centre tap (1025) is electrically connected to the first portion (713) of its respective winding by a first vertical centre tap connector (1031) and to the second portion (711) of its respective winding by a second vertical centre tap connector (1032), and the other centre tap (1026) is electrically connected to the first portion (712) of its respective winding by third (1033) and fourth (1034) vertical centre tap connectors and to the second portion (1014) of its respective winding by fifth (1035) and sixth (1036) vertical centre tap connectors.

13. The integrated circuit based transformer of claim 11 or 12, wherein at least one of the vertical connectors (1031, 1035, 1036) used to electrically connect a centre tap to its respective winding passes through a hole formed in the other winding.

14. The integrated circuit based transformer of any of claims 10 to 13, wherein one of the centre taps (1025) has a linear configuration comprising an elongate element (1027) and the other centre tap (1026) has a forked configuration comprising first (1028) and second (1029) prongs, and wherein the centre taps (1025, 1026) are electrically connected to their respective windings such that the first (1028) and second (1029) prongs of the forked centre tap (1026) are positioned symmetrically on either side of the elongate element (1027) of the linear centre tap (1025).

15. An oscillator circuit comprising the integrated circuit based transformer of any preceding claim.

Figure 1

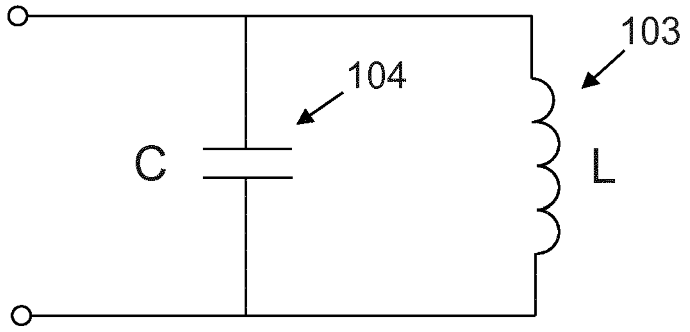


Figure 2

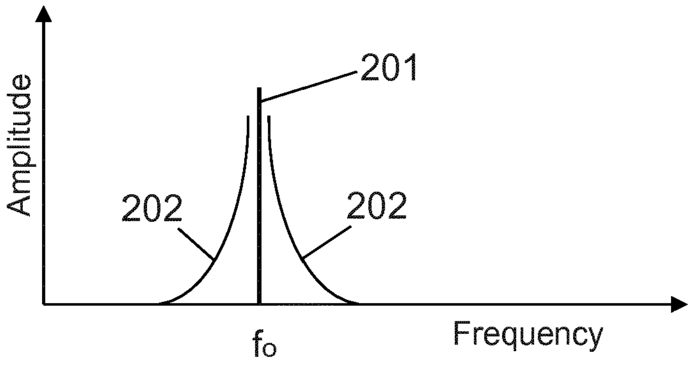


Figure 3

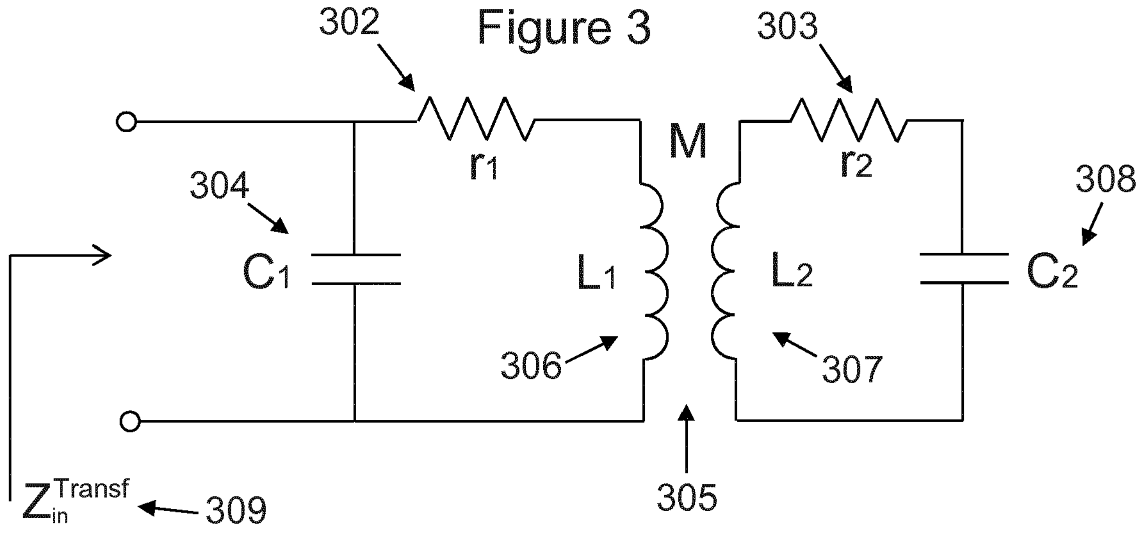


Figure 4

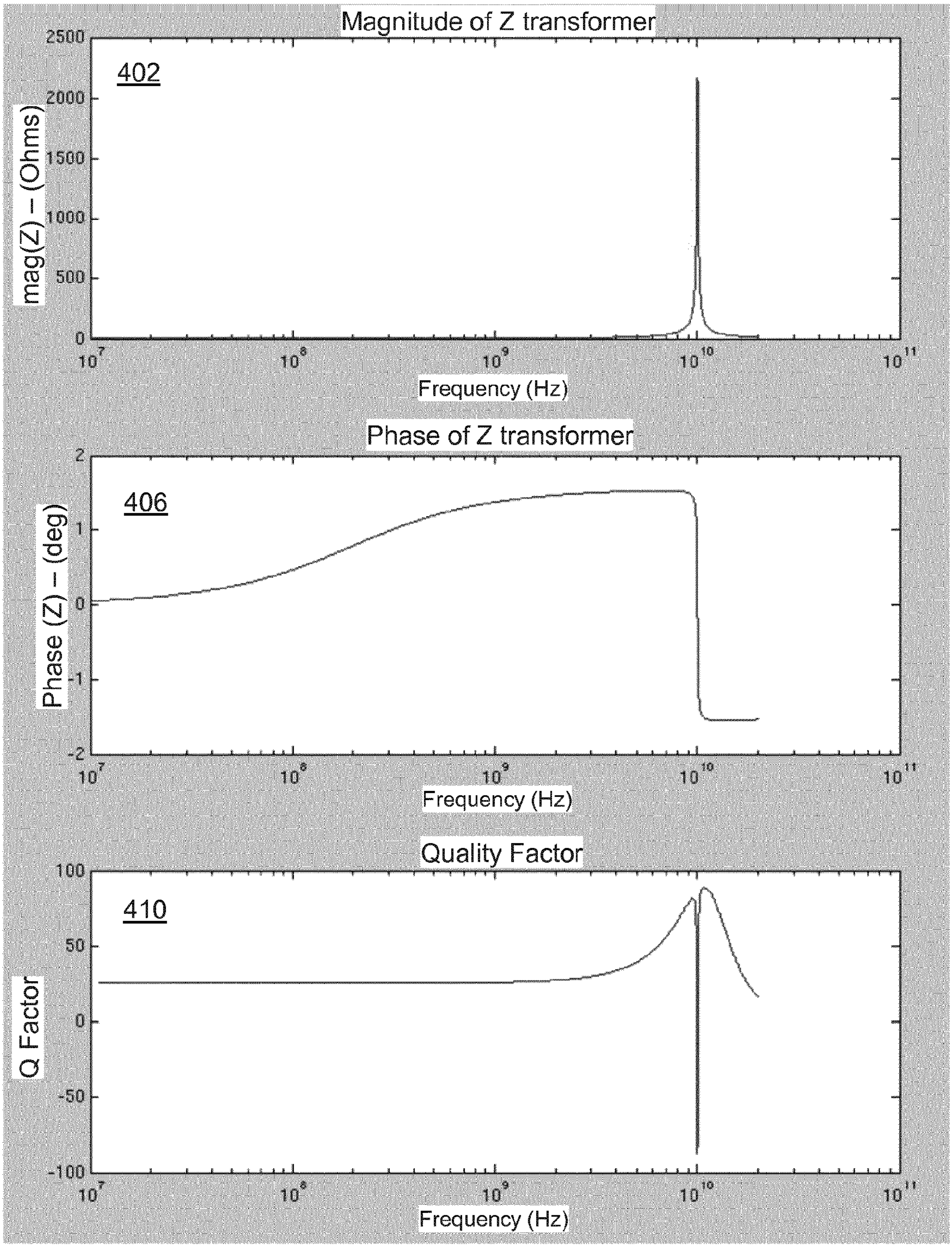

Magnitude of Z transformer
402
mag(Z) – (Ohms)
2500
2000
1500
1000
500
0
10^7
10^8
10^9
10^{10}
10^{11}
Frequency (Hz)
Phase of Z transformer
406
Phase (Z) – (deg)
2
1
0
-1
-2
10^7
10^8
10^9
10^{10}
10^{11}
Frequency (Hz)
Quality Factor
410
Q Factor
100
50
0
-50
-100
10^7
10^8
10^9
10^{10}
10^{11}
Frequency (Hz)

Figure 5

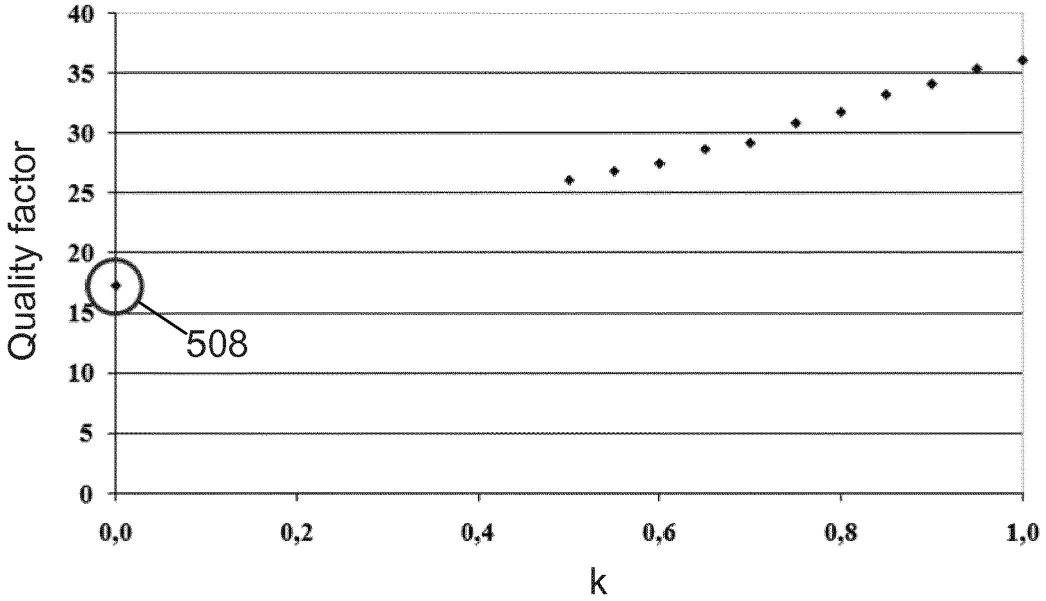


Figure 6

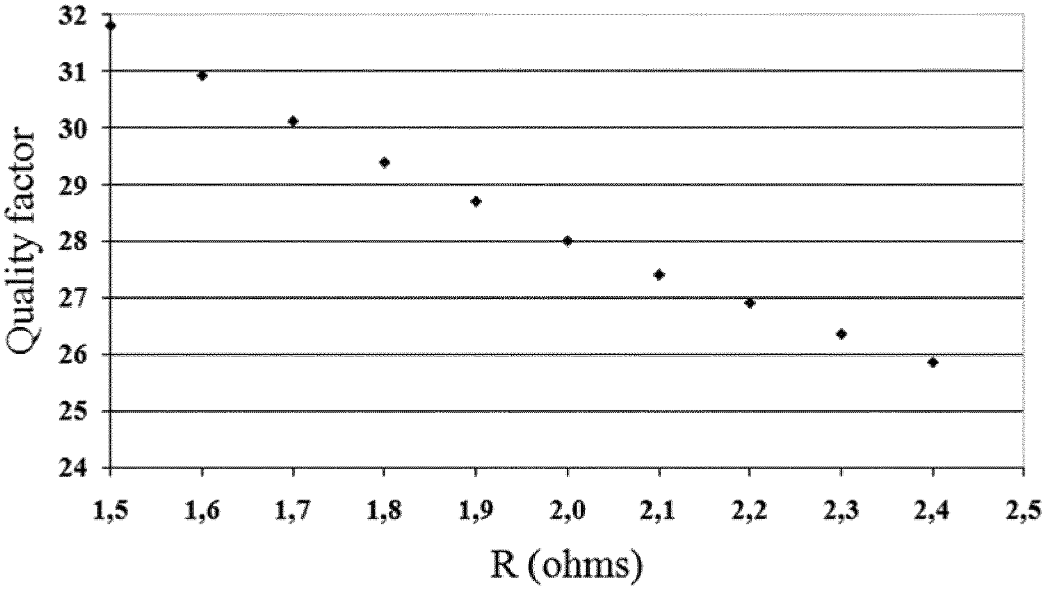


Figure 7a

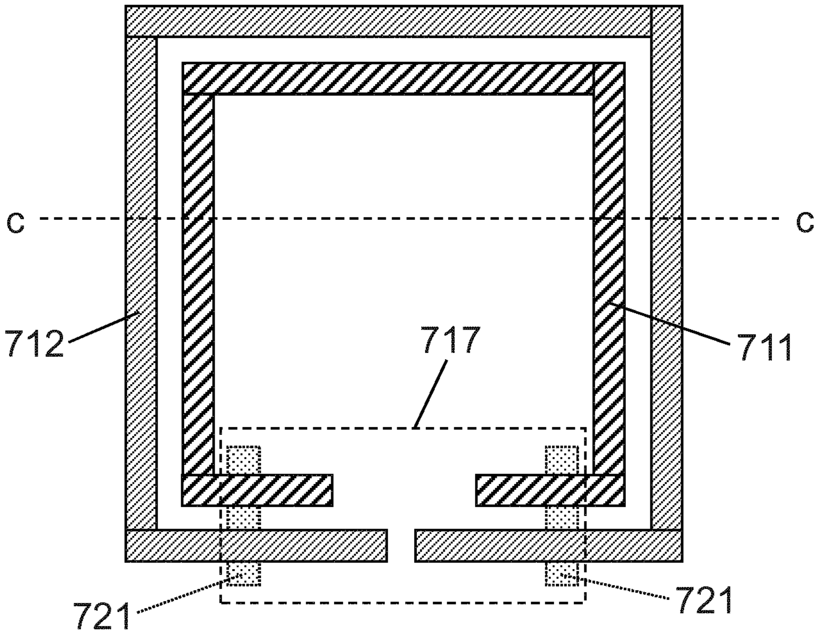


Figure 7b

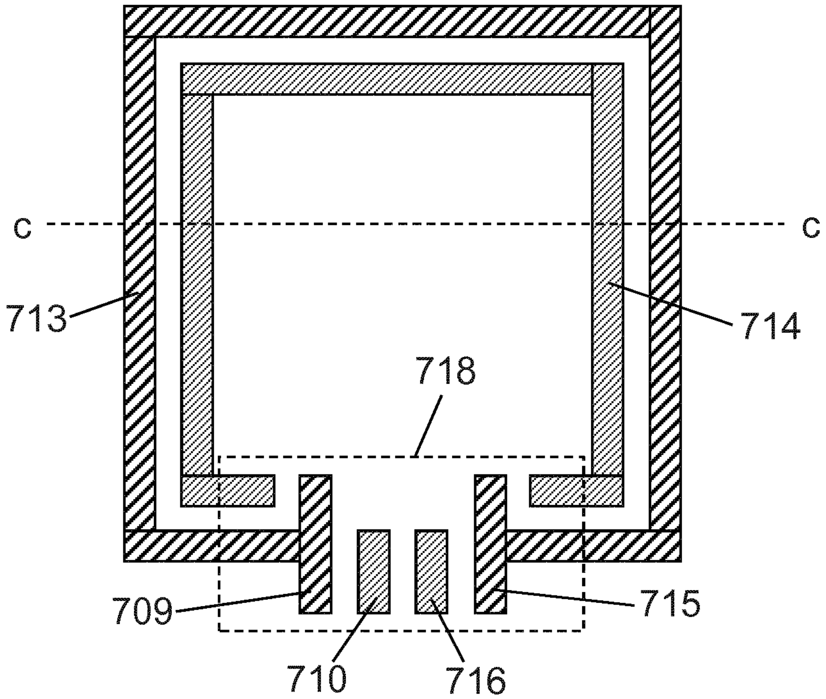


Figure 7c

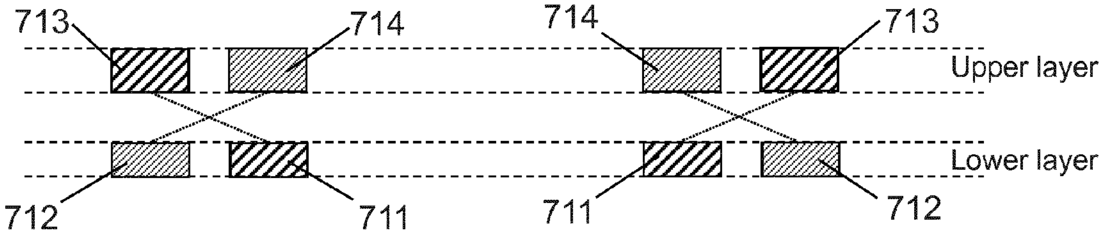


Figure 8a

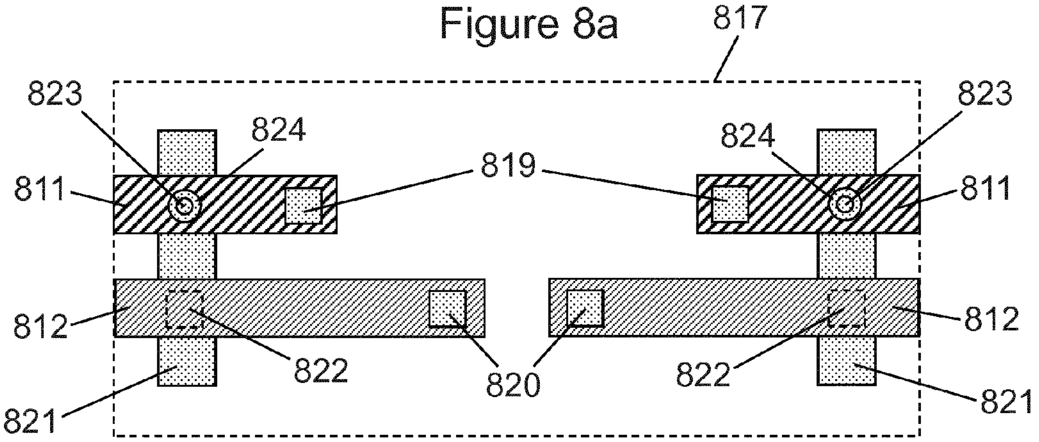


Figure 8b

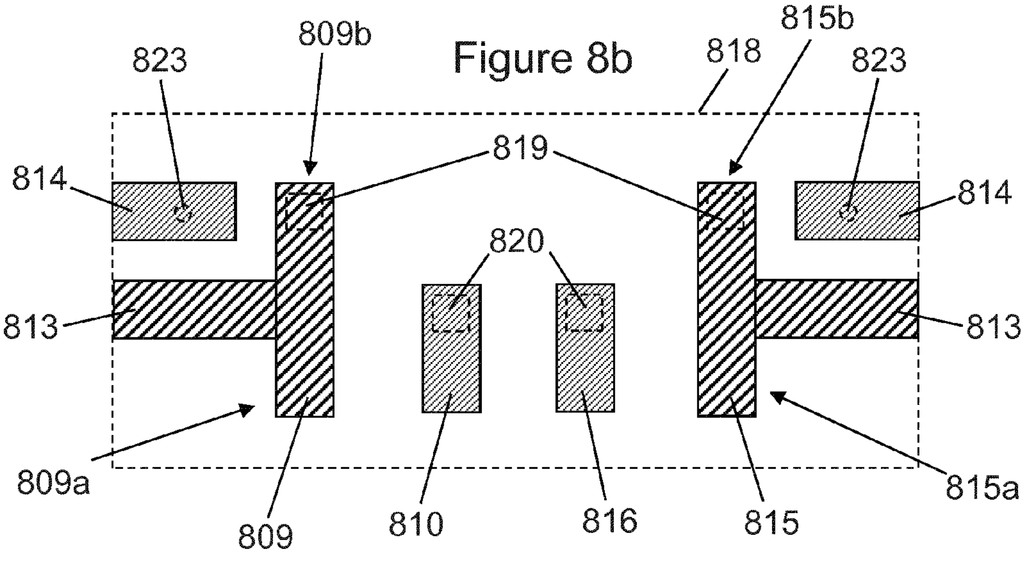


Figure 9a

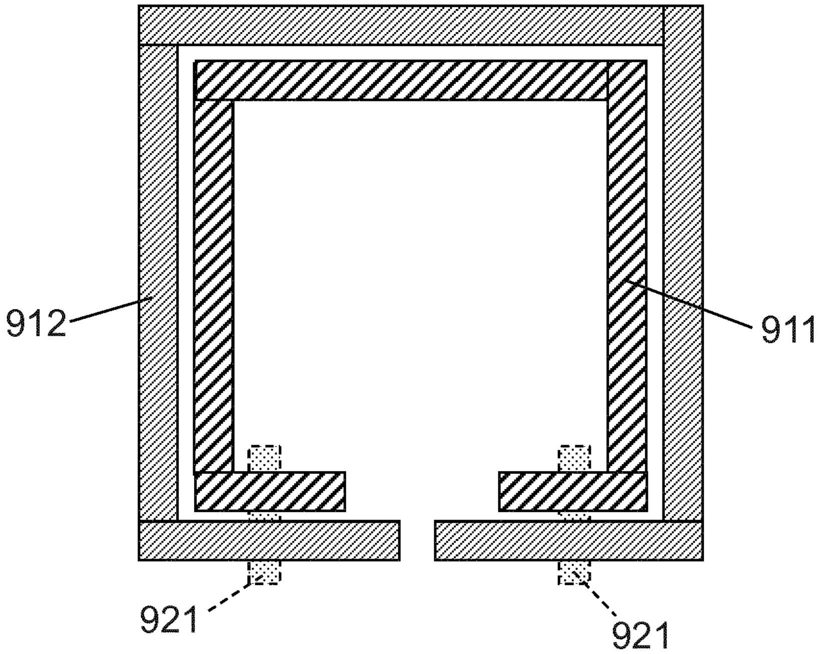


Figure 9b

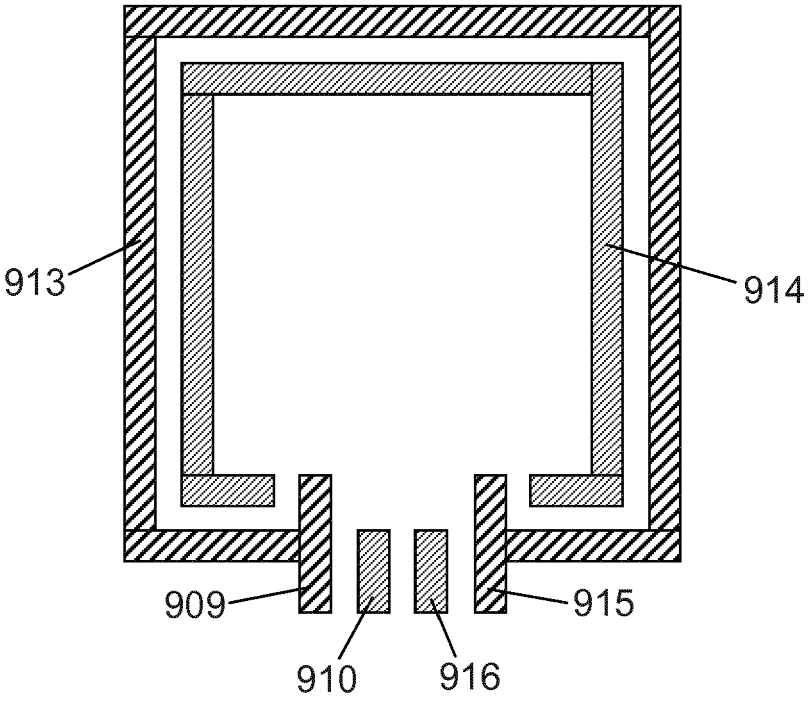


Figure 10a

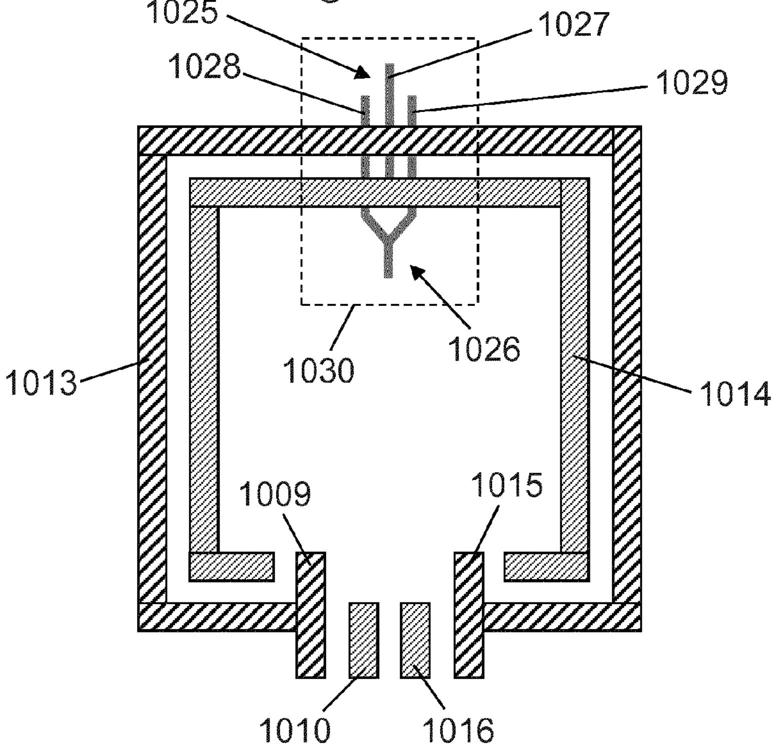


Figure 10b

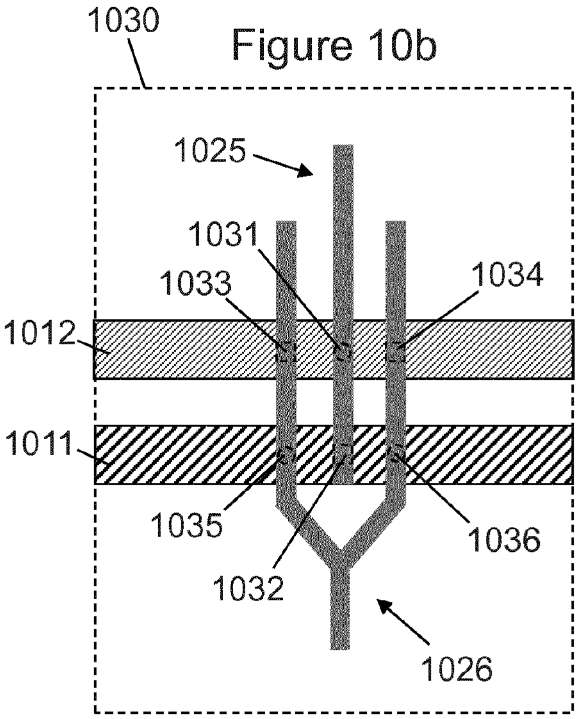
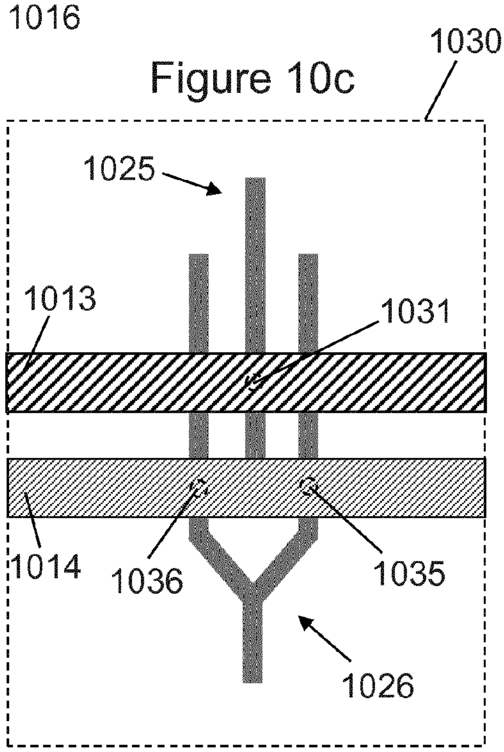


Figure 10c



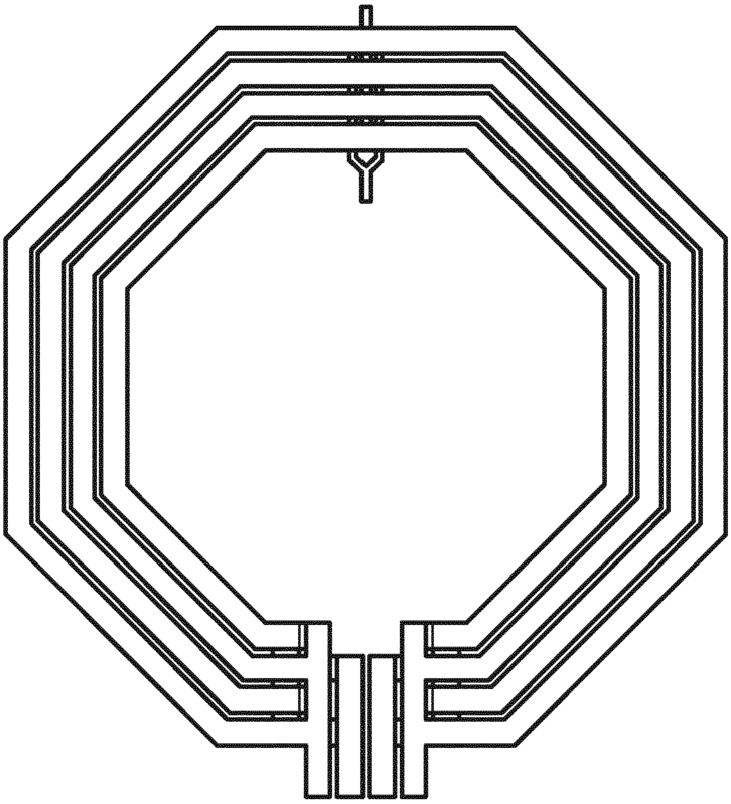


FIG. 10d

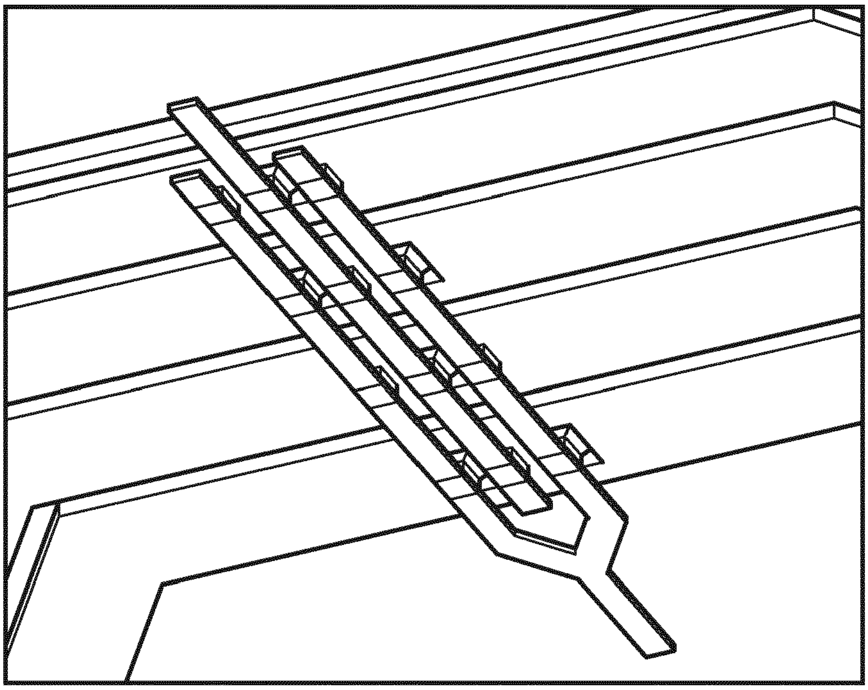


FIG. 10e

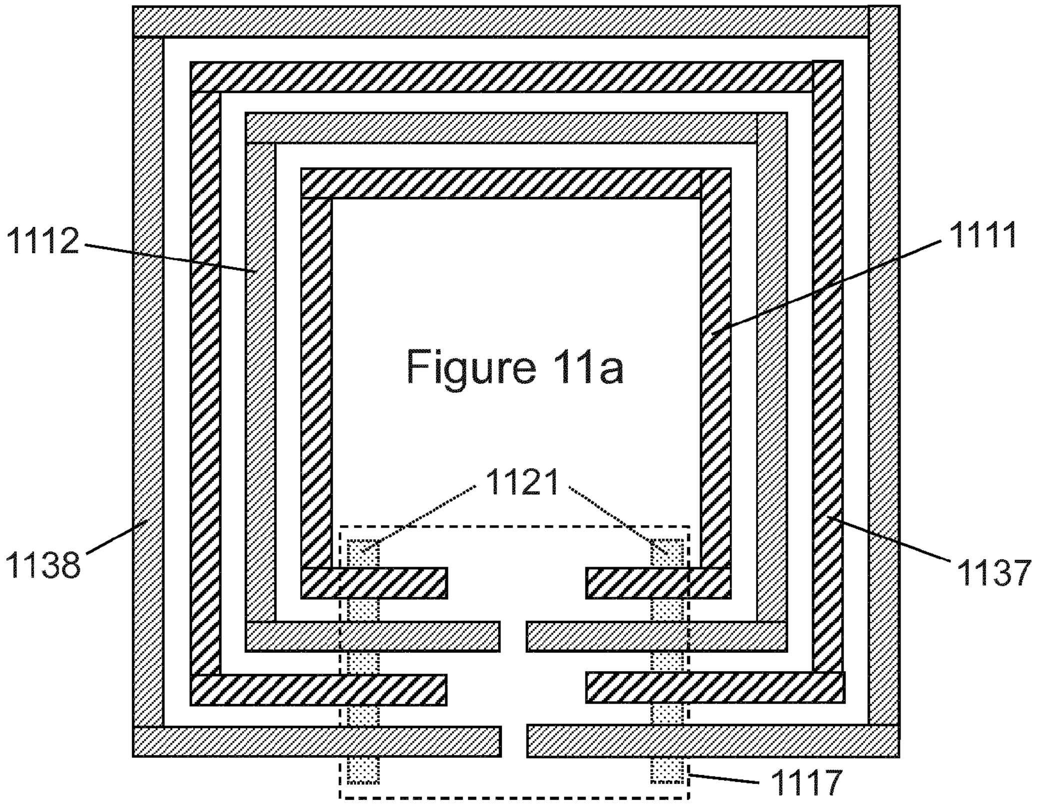


Figure 11a

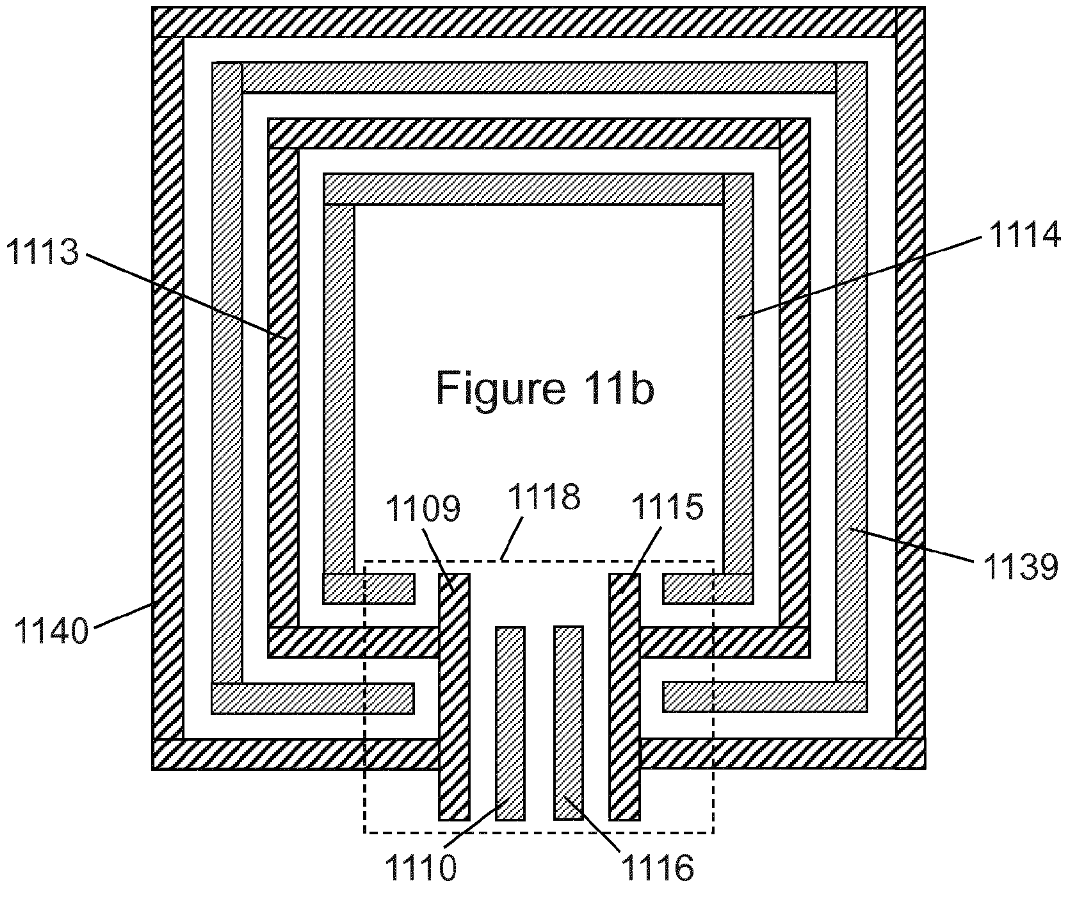


Figure 11b

Figure 11c

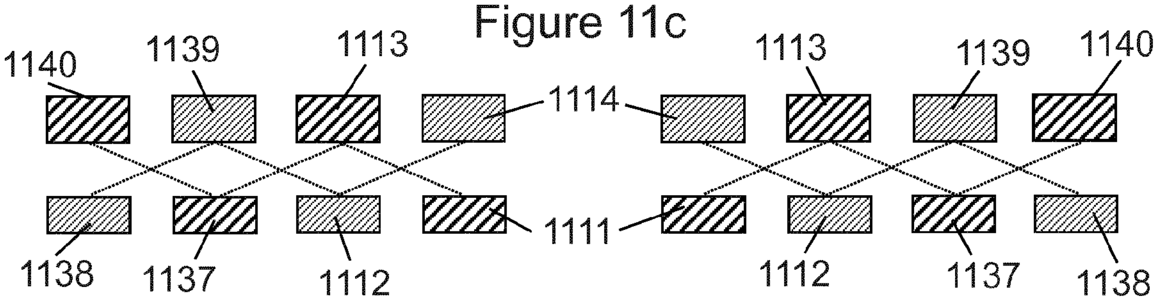


Figure 12a

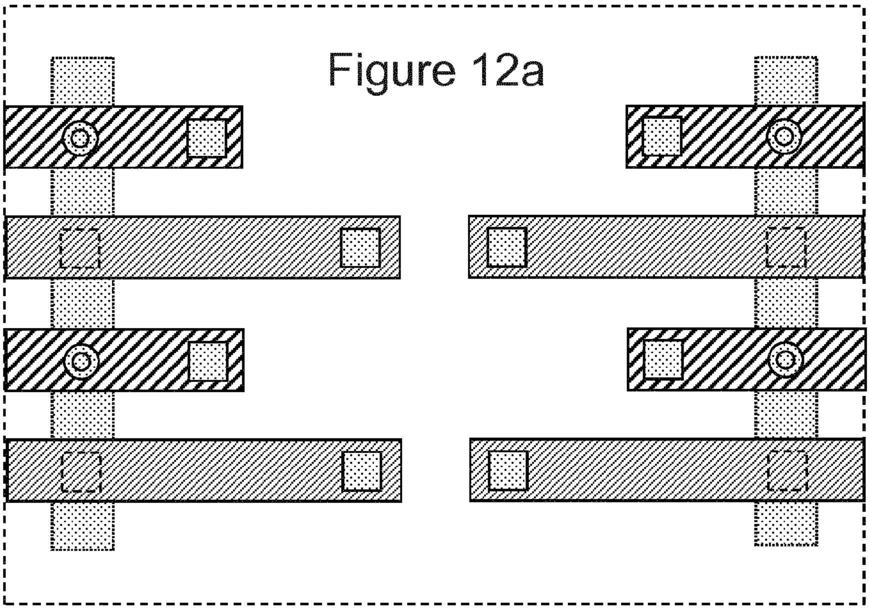


Figure 12b

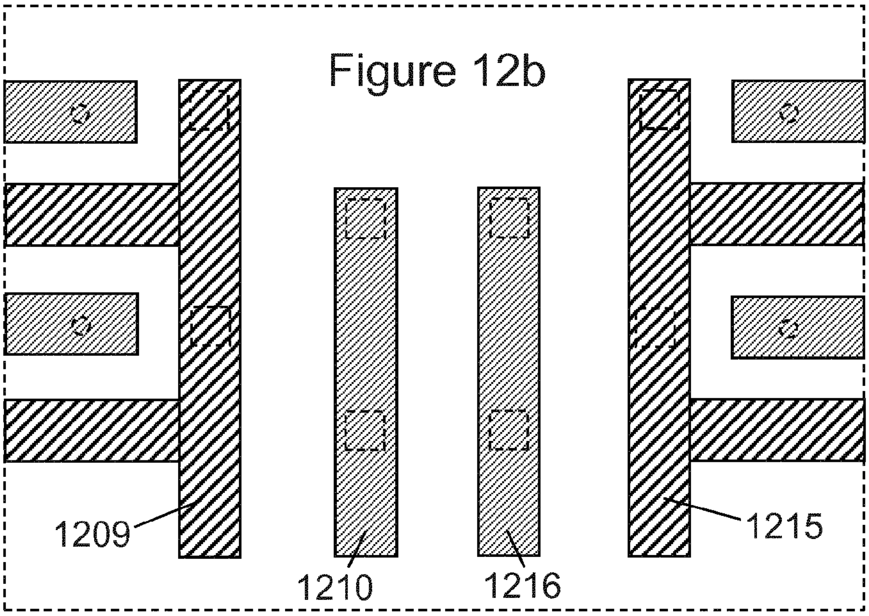


Figure 13

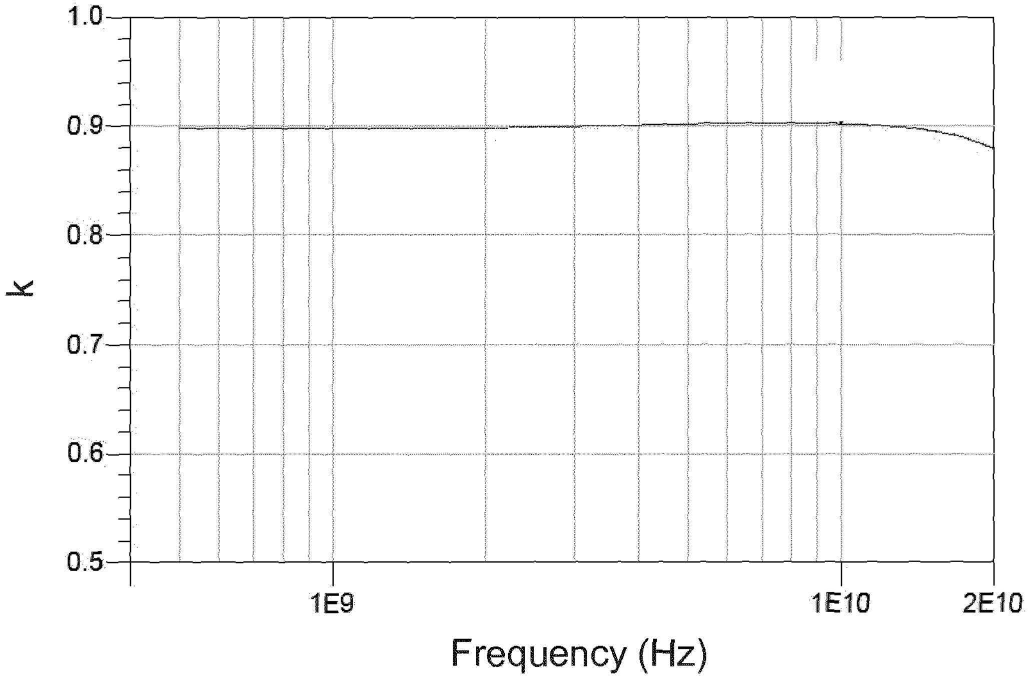


Figure 14

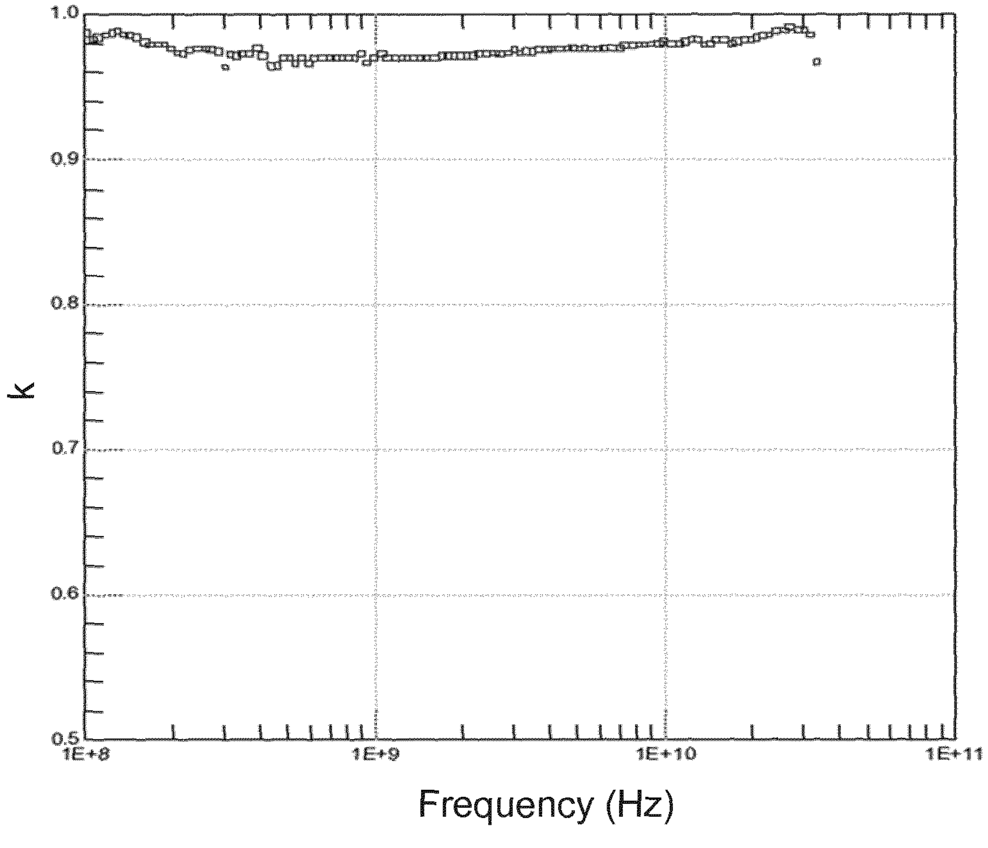


Figure 15

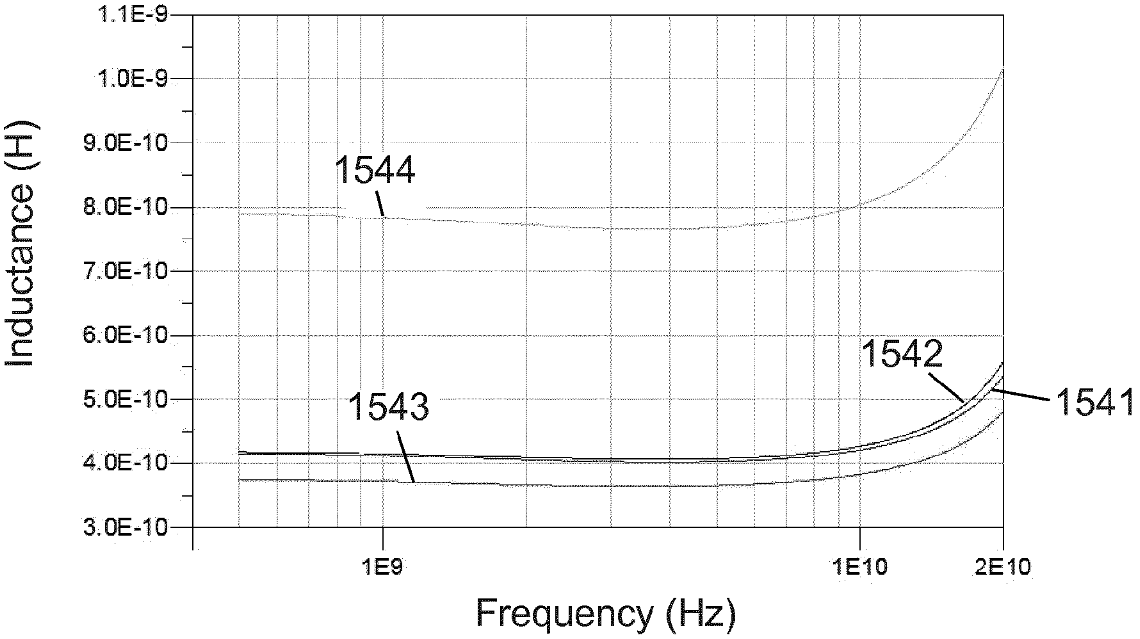


Figure 16

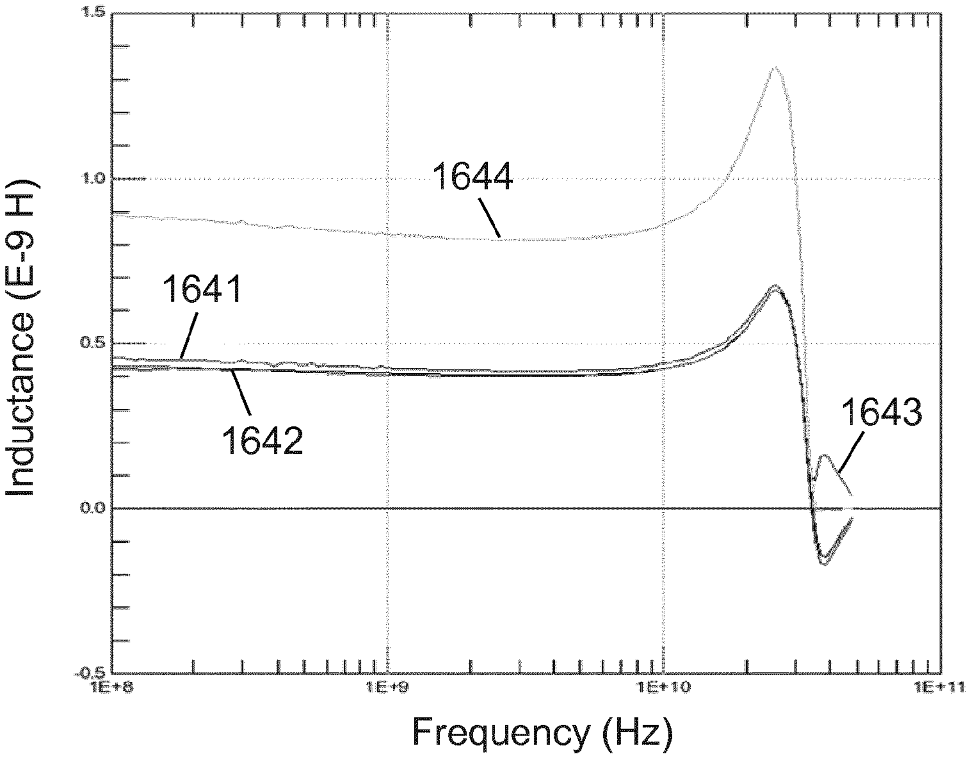


Figure 17

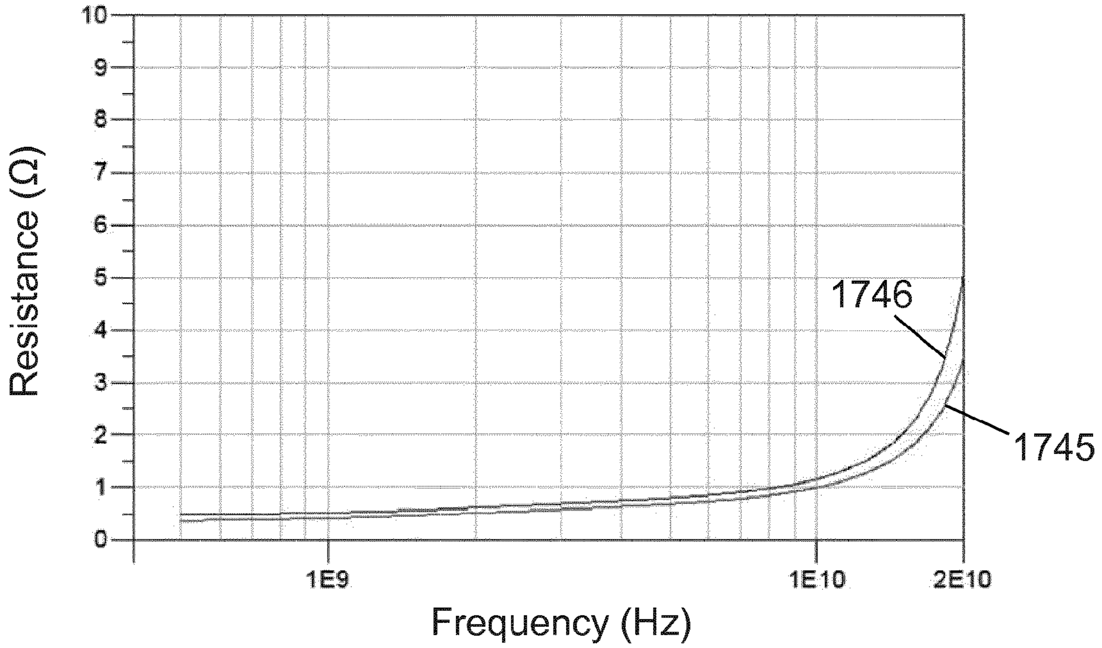


Figure 18

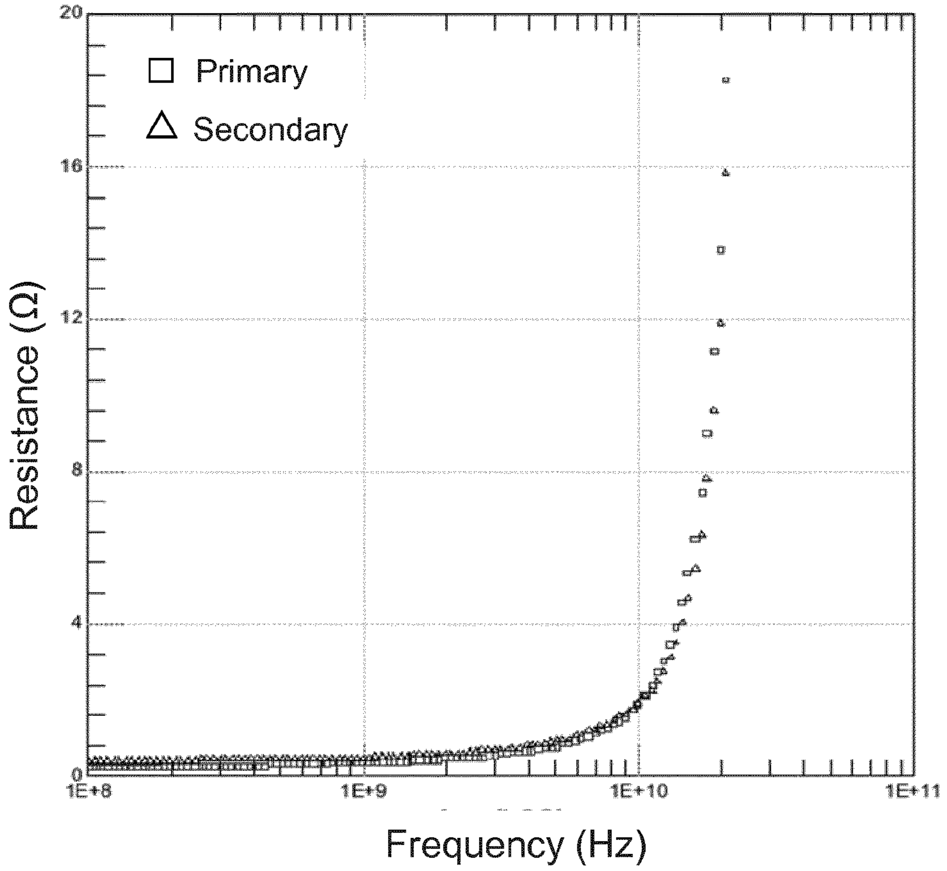


Figure 19

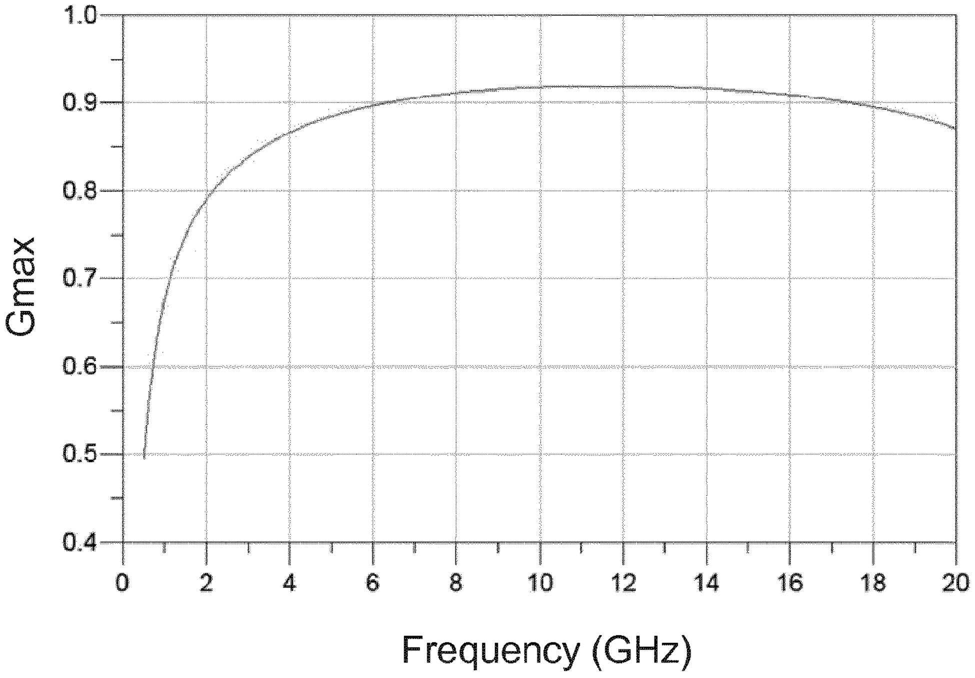


Figure 20

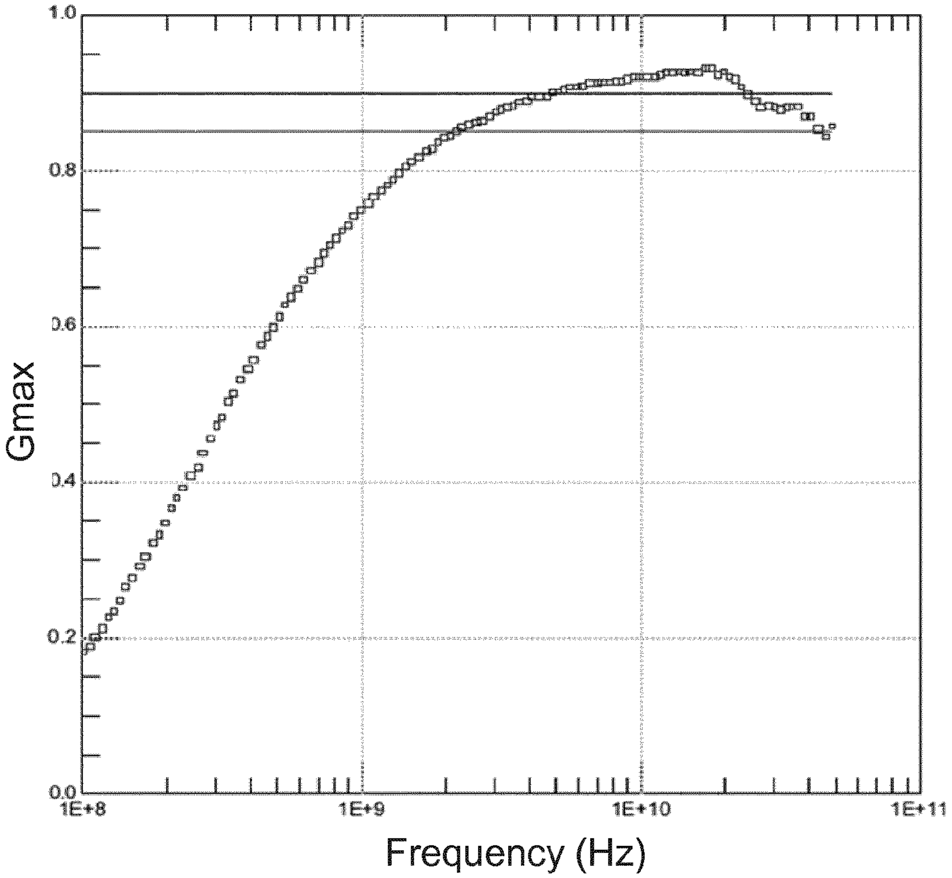
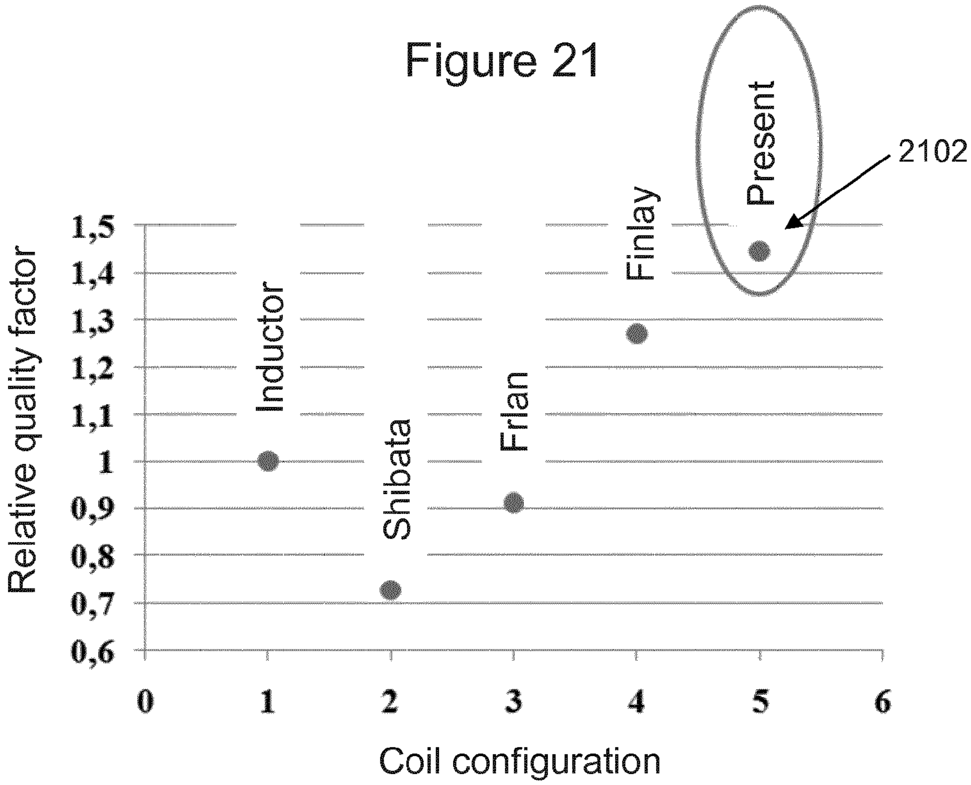


Figure 21



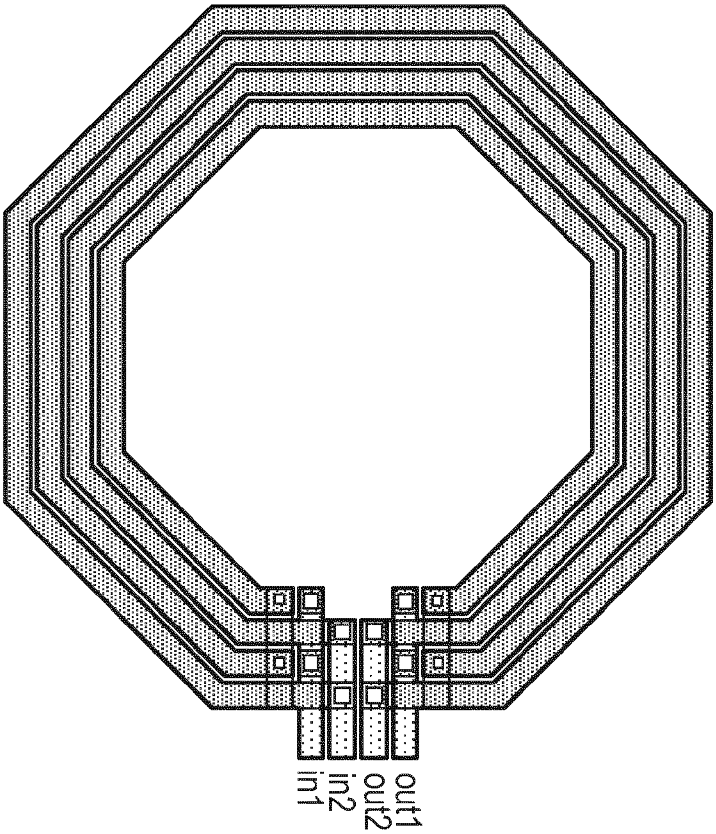


FIG. 22

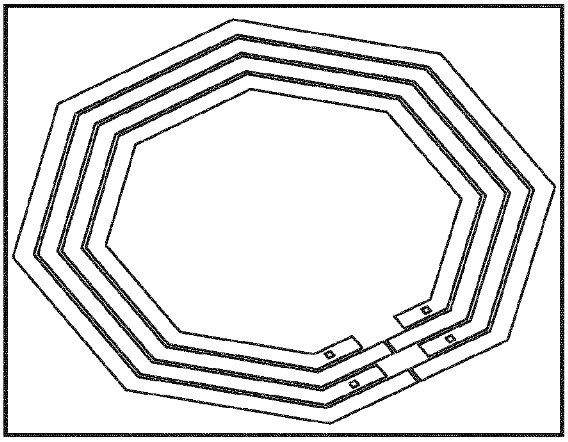


FIG. 23a

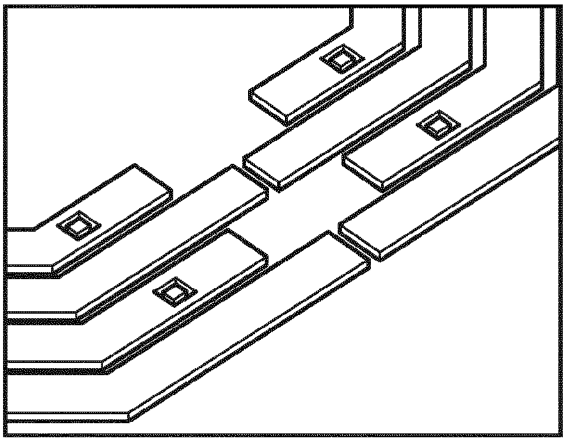


FIG. 23b

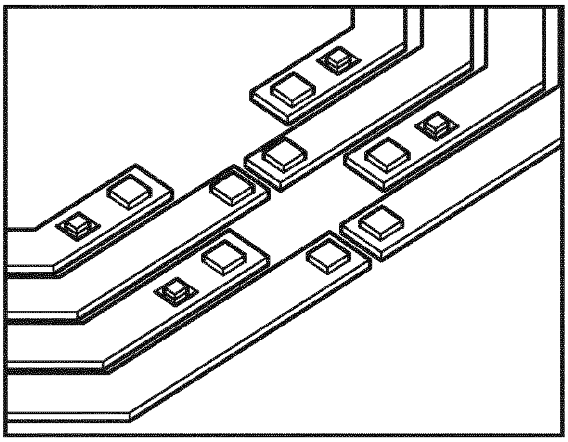


FIG. 23c

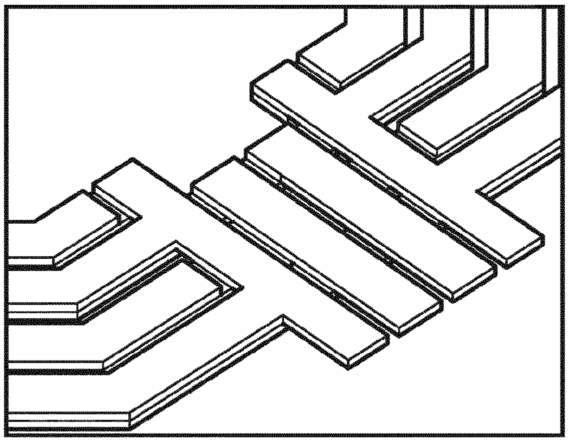


FIG. 23d

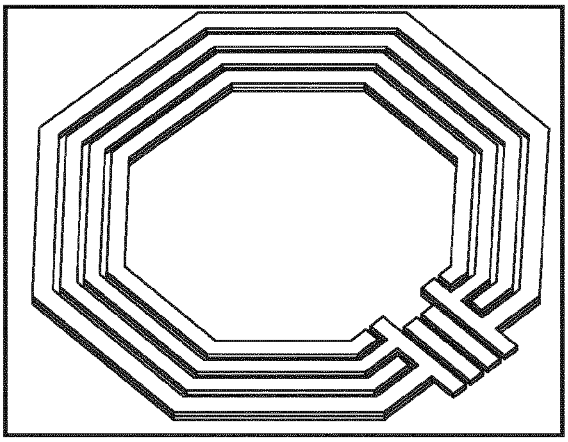


FIG. 23e

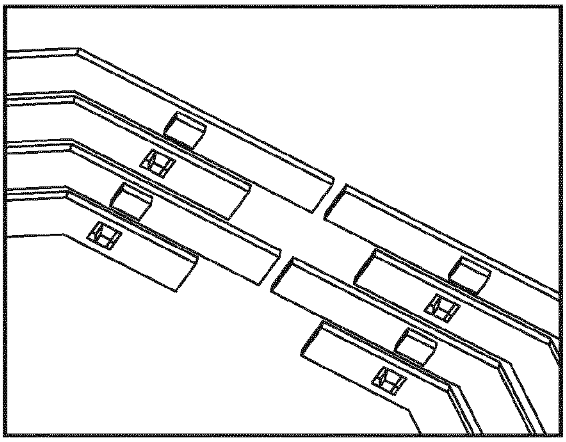


FIG. 23f

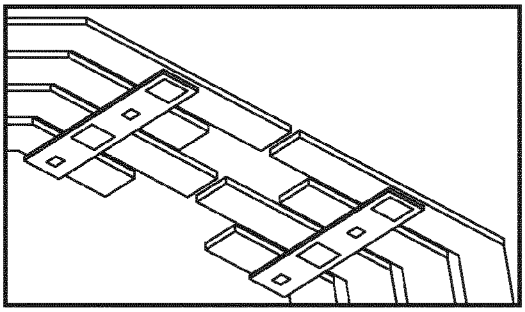


FIG. 23g

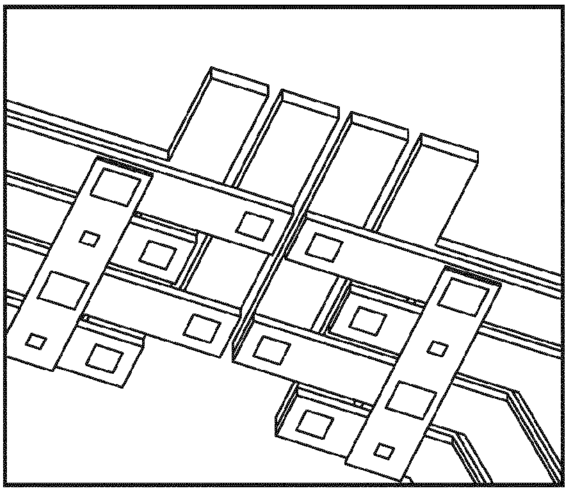


FIG. 23h

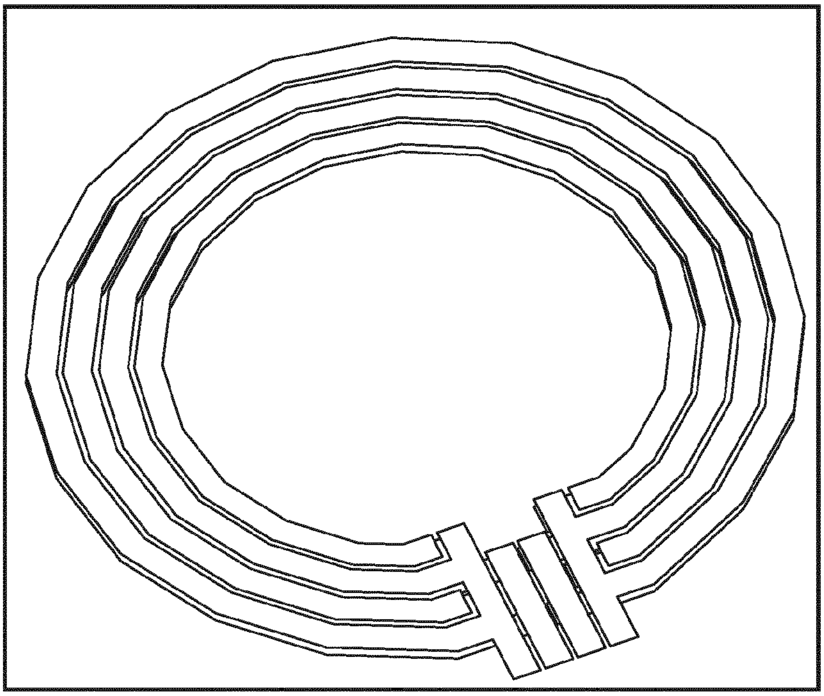


FIG. 24

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EUROPEAN SEARCH REPORT

Application Number
EP 12 29 0176

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X Y A	US 2009/284339 A1 (CHOI TAE-HOON [KR] ET AL) 19 November 2009 (2009-11-19) * abstract * * page 1, paragraph 7-9 * * page 2, paragraph 54 - page 8, paragraph 9 * * figures 1-18 * -----	1-4,6, 10,11,15 5,7,8 12-14	INV. H01F27/28 H01F21/12
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X	US 2010/164667 A1 (HO-HSIANG CHEN [TW]) 1 July 2010 (2010-07-01) * abstract * * page 2, paragraph 28 - page 4, paragraph 46 * * figures 1-12 * -----	1,3,4,6, 9,10,15	**TECHNICAL FIELDS SEARCHED (IPC)** H01F
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Place of search	Date of completion of the search	Examiner
Munich	4 March 2013	Kardinal, Ingrid

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1

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EUROPEAN SEARCH REPORT

Application Number
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Y	WO 2008/123082 A1 (NEC CORP [JP]; TANABE AKIRA [JP]) 16 October 2008 (2008-10-16) * abstract; figures 15A,15B * -----	5	
Y	US 2008/094166 A1 (HSU TSUN-LAI [TW] ET AL) 24 April 2008 (2008-04-24) * abstract * * page 3, paragraph 43 - page 5, paragraph 60 * * figures 4,5 * -----	7,8	TECHNICAL FIELDS SEARCHED (IPC)
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Munich	4 March 2013	Kardinal, Ingrid

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