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(54) MULTI-PHASE INTEGRATED COUPLED INDUCTOR STRUCTURE

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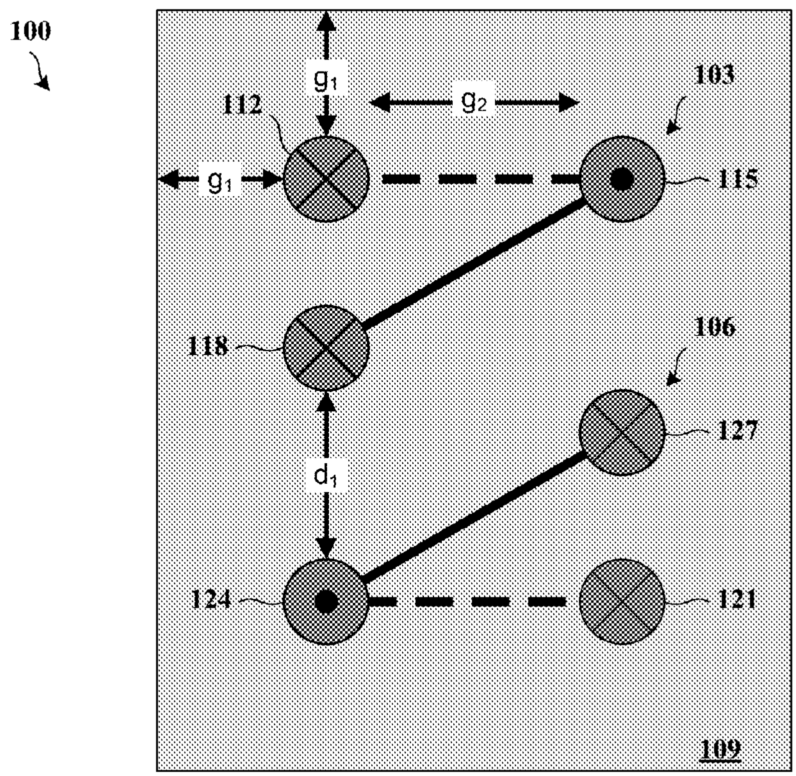
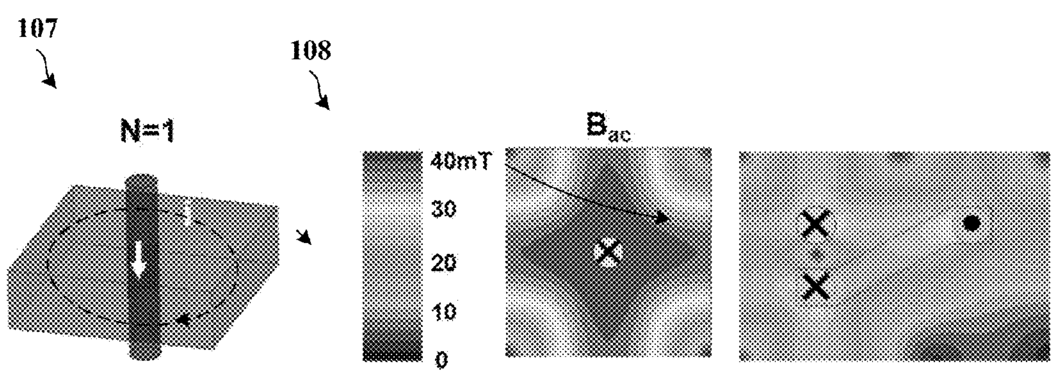
CPC ***H01F 27/24*** (2013.01); ***H01F 27/42*** (2013.01); ***H01F 27/2804*** (2013.01); ***H01F 27/40*** (2013.01)

(57) ABSTRACT

Aspects of multi-phase integrated coupled inductors are described. In one embodiment, a multi-phase integrated coupled inductor includes a magnetic core and a coupled set of inductors. Each inductor can include conductive vias that are asymmetrically distributed in two symmetrical core slots in the magnetic core, so that each inductor has a different number of lateral-flux vias in each slot.





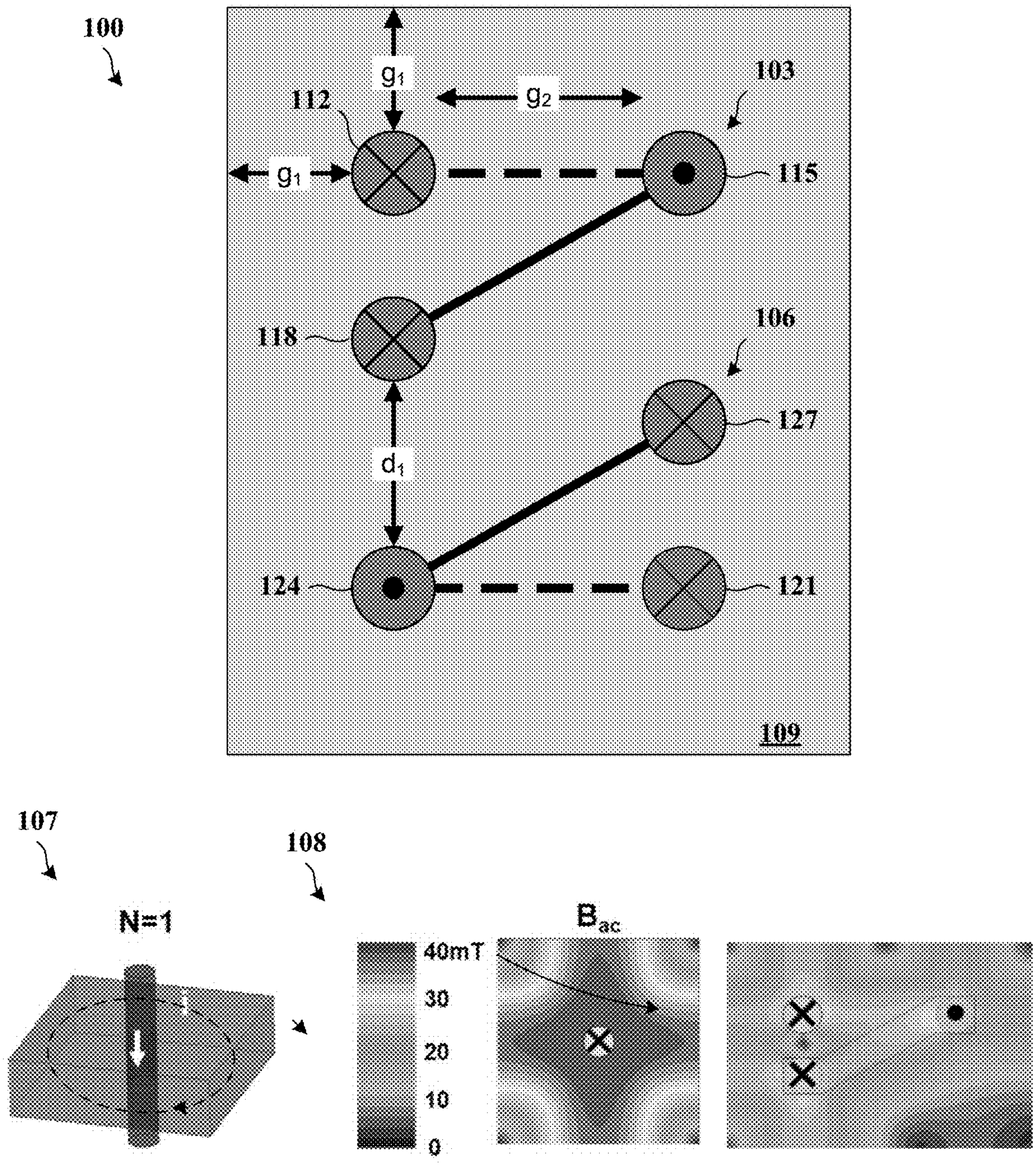
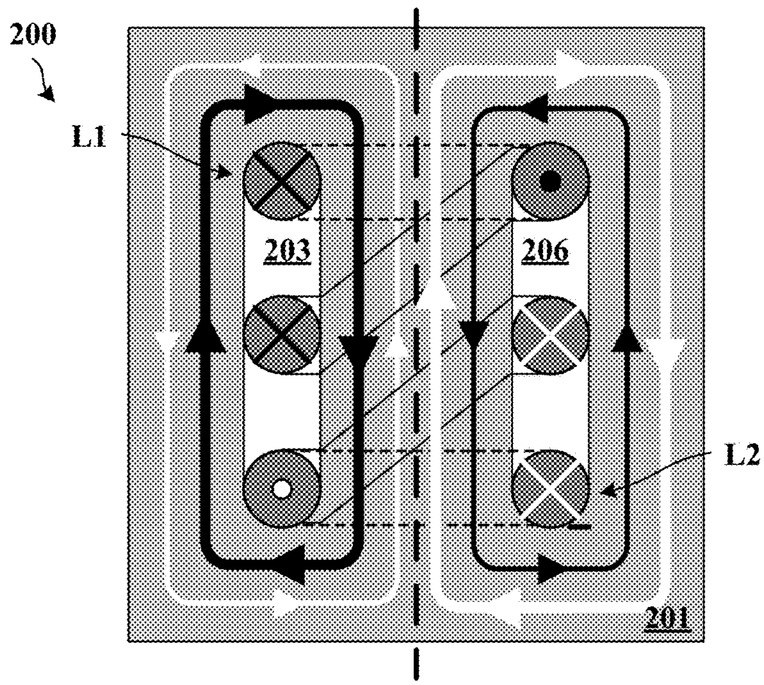

100
g1
g2
112
103
115
118
106
127
d1
124
121
109
107
N=1
108
Bac
40mT
30
20
10
0

FIG. 1


200
L1
203
206
L2
201

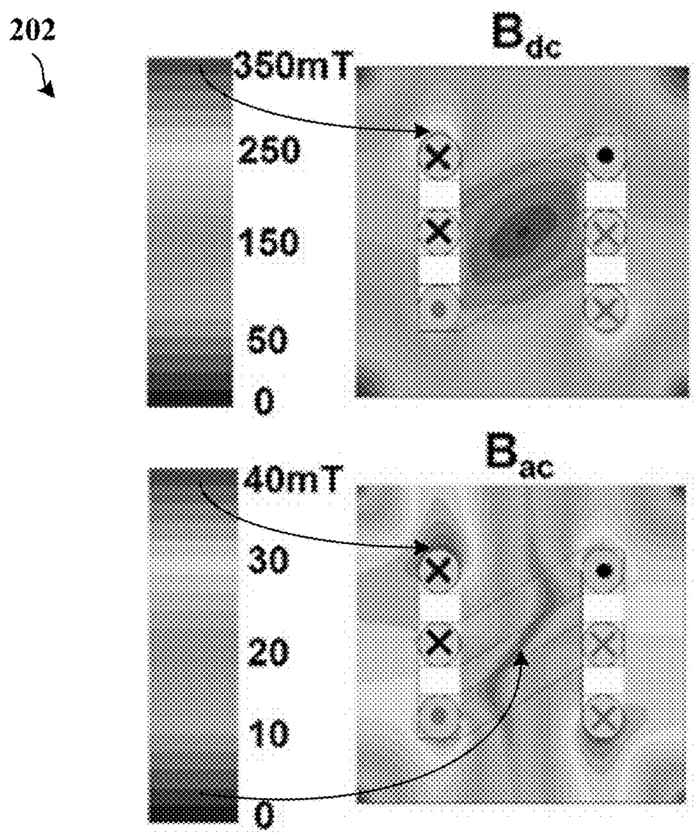

202
B_{dc}
350mT
250
150
50
0
B_{ac}
40mT
30
20
10
0

FIG. 2

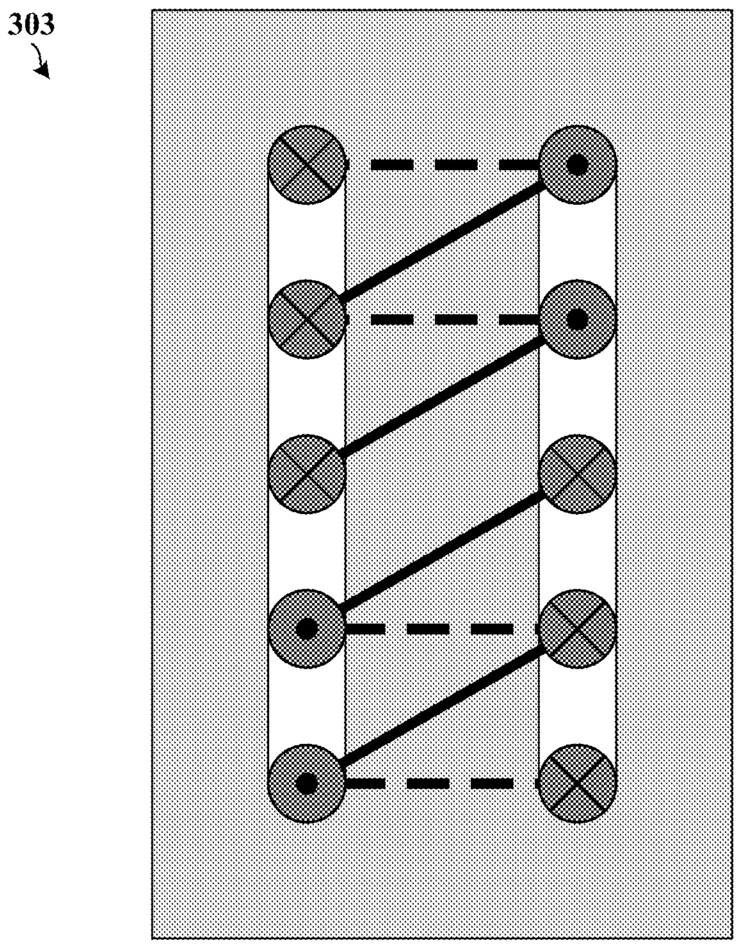
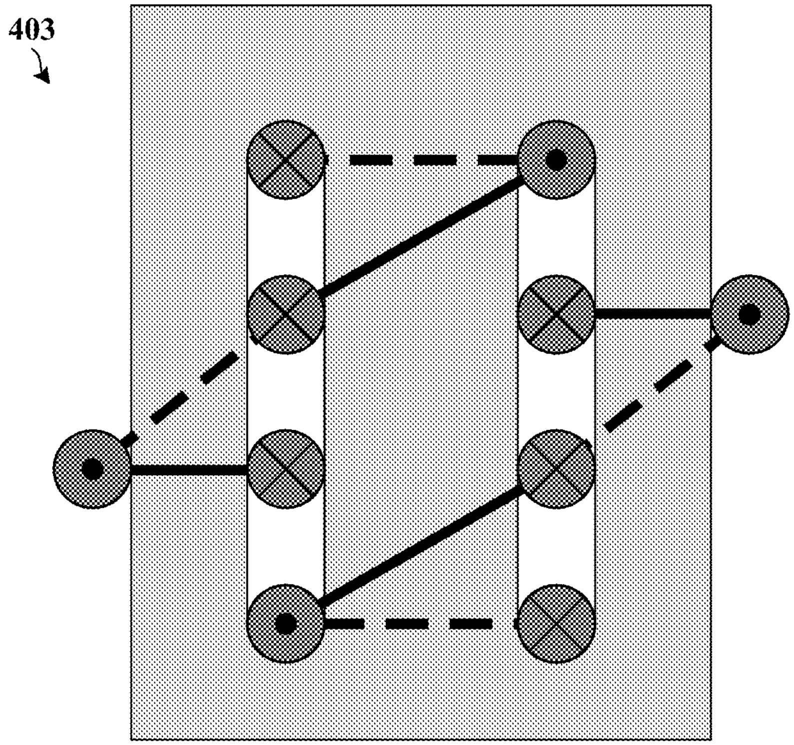


FIG. 3



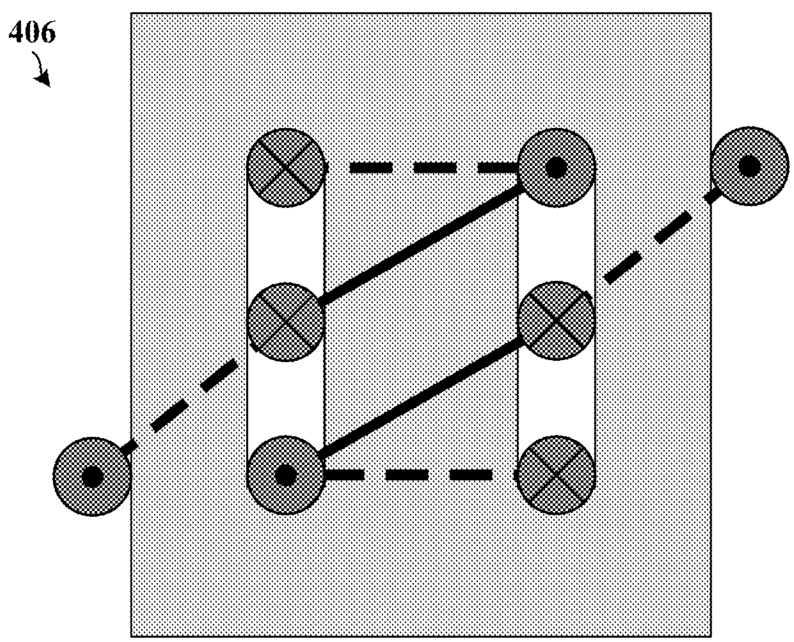


FIG. 4

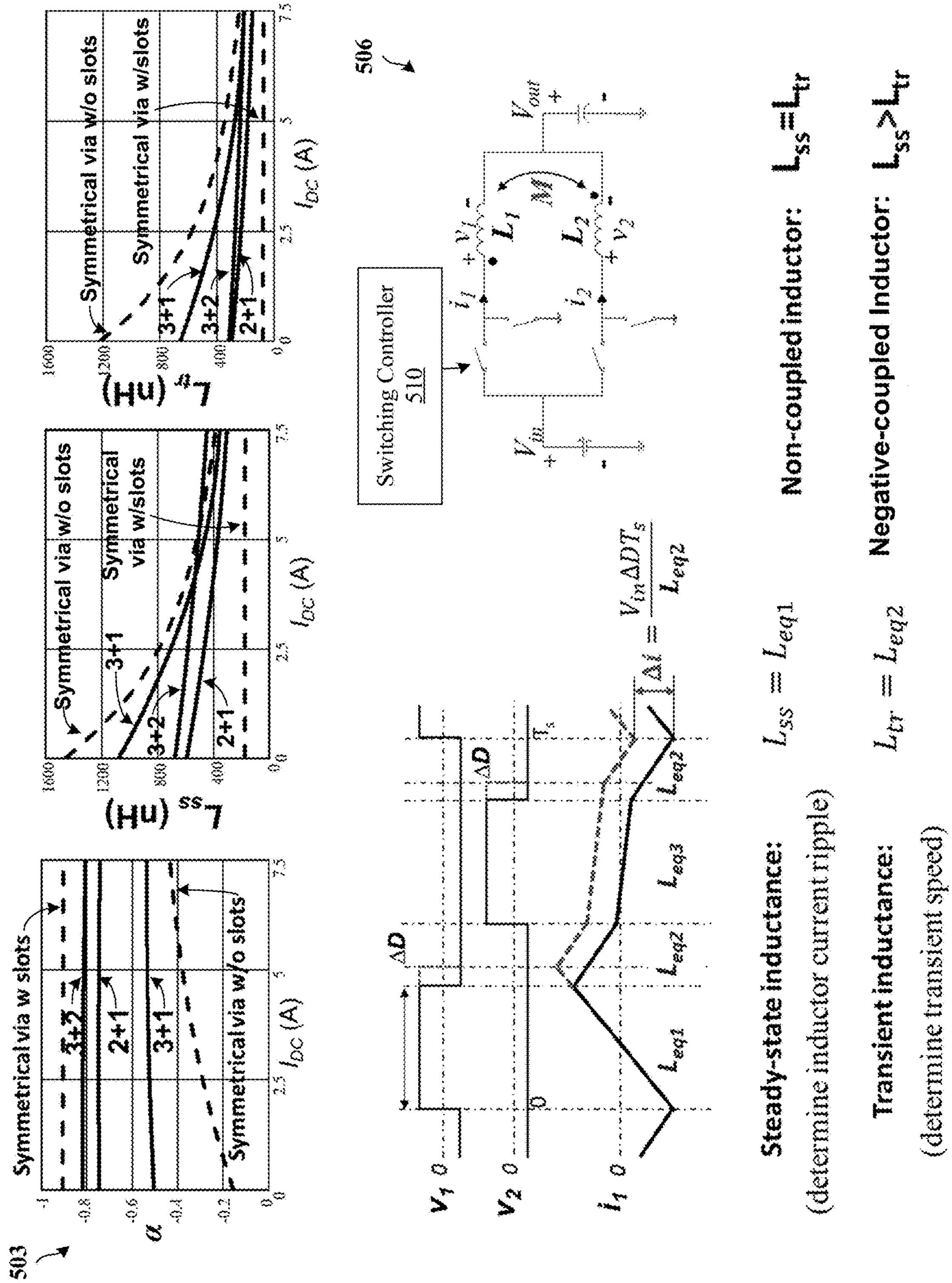

503
Symmetrical via w slots
3+2
2+1
3+1
Symmetrical via w/o slots
α
I_{DC} (A)
L_{ss} (nH)
Symmetrical via w/o slots
Symmetrical via w/slots
3+1
3+2
2+1
L_{tr} (nH)
Symmetrical via w/o slots
Symmetrical via w/slots
3+1
3+2
2+1
506
Switching Controller
510
V_{in}
V_{out}
i_1
i_2
L_1
L_2
v_1
v_2
M
v_1 0
v_2 0
i_1 0
ΔD
ΔD
T_s
L_{eq1}
L_{eq2}
L_{eq3}
L_{eq2}
$\Delta I = \frac{V_{in}\Delta D T_s}{L_{eq2}}$
Steady-state inductance:
(determine inductor current ripple)
$L_{ss} = L_{eq1}$
Transient inductance:
(determine transient speed)
$L_{tr} = L_{eq2}$
Non-coupled inductor: $L_{ss}=L_{tr}$
Negative-coupled Inductor: $L_{ss}>L_{tr}$

FIG. 5

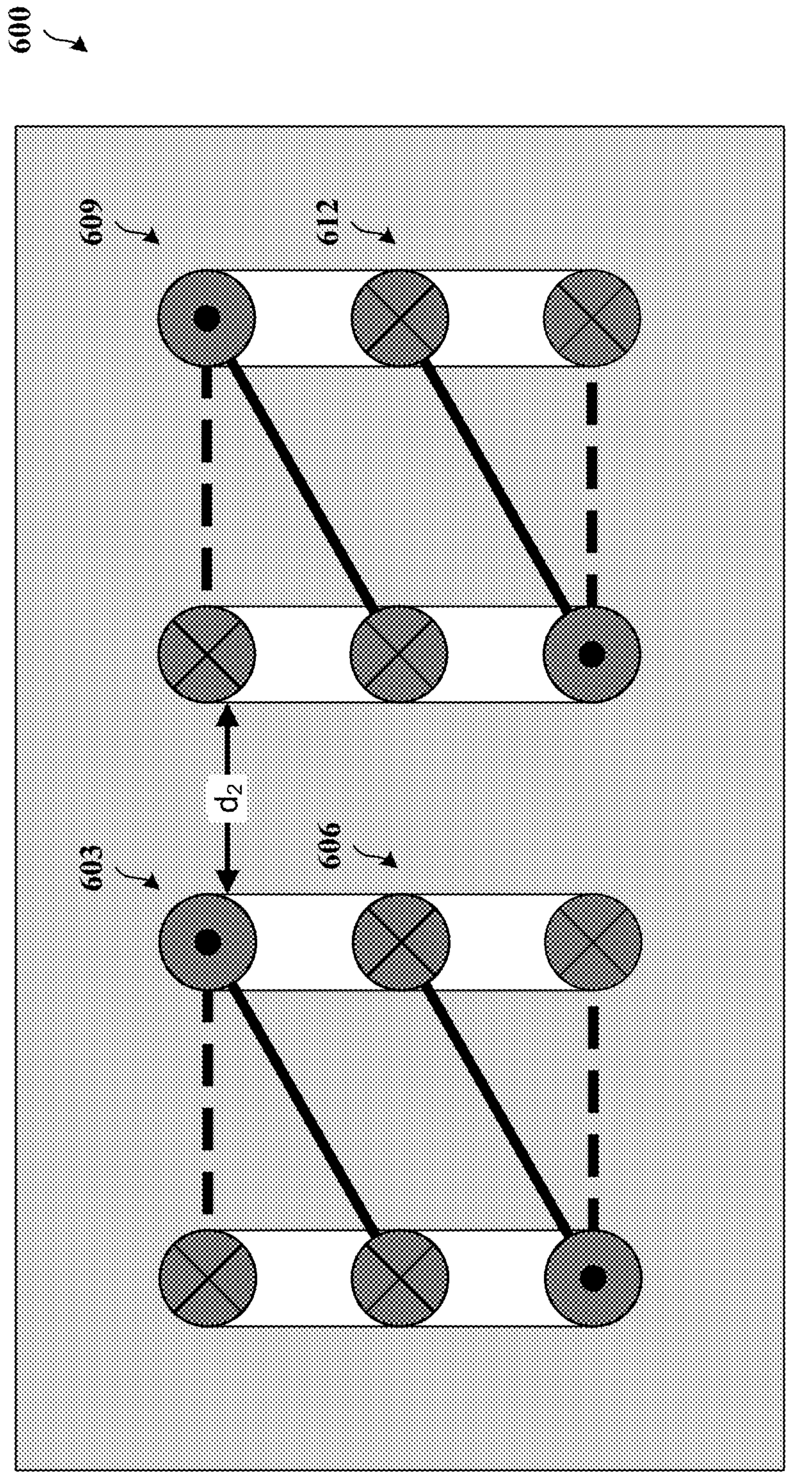


FIG. 6

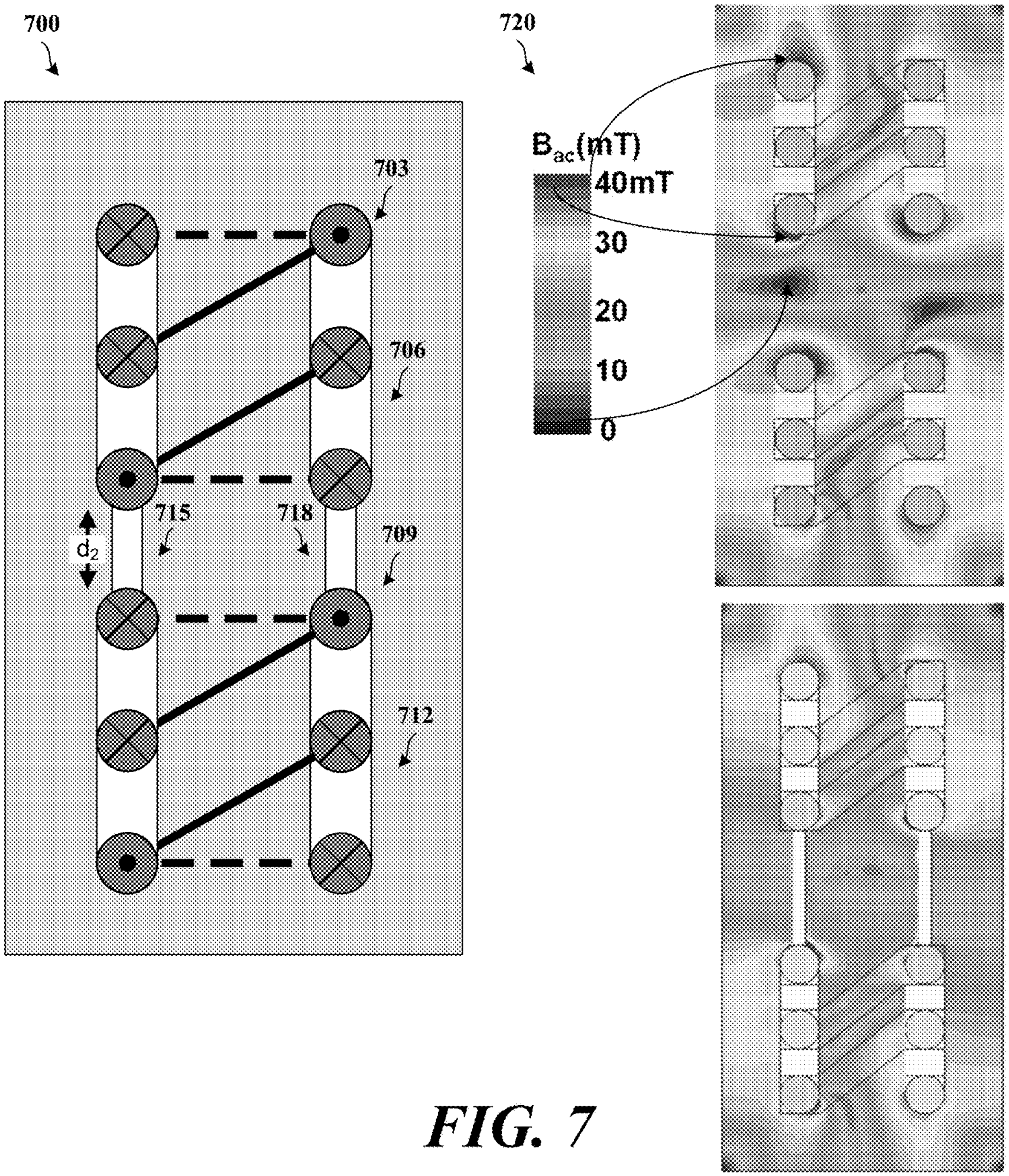


FIG. 7

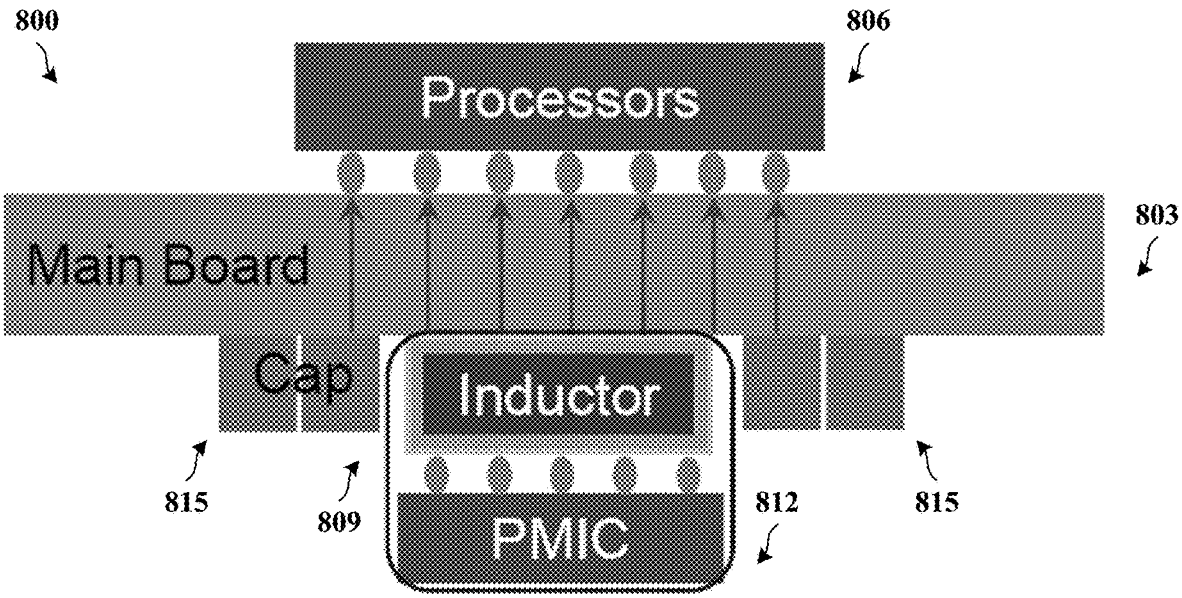

800
806
Processors
Main Board
803
Cap
Inductor
PMIC
815
809
812
815

FIG. 8

MULTI-PHASE INTEGRATED COUPLED INDUCTOR STRUCTURE

BACKGROUND

[0001] DC-DC step-down converters, especially buck converters, are widely used in many digital devices such as servers, telecoms, laptops, desktops, smartphones and so on. In most devices, multiphase buck converters are used to provide enough power to digital loads, and each buck converter requires one inductor. Compared with non-coupled inductors, negative coupled inductors can realize small current ripple and fast transient speed at the same time, which is preferred from a circuit performance point of view. On the other hand, negative coupling can reduce the DC flux in the magnetic core. Therefore, higher inductor current can be applied without magnetic core saturation. As the development of central processing units (CPUs) and graphics processing units (GPUs) in digital devices continuously grows, the power demand of digital devices is becoming higher and higher. As a result, more phases can be added to converters to meet high power demand. Meanwhile, small inductor size and low profile are becoming more and more critical for inductor design, due to limited space in digital devices.

[0002] Some negative coupled inductors can include pieces of magnetic core, and each magnetic piece can wrap two conductors. Each phase inductor is negatively coupled to another two inductors. While negative coupling can help to reduce DC flux in the magnetic core, existing structures can require one piece of magnetic core for each phase, which increases manufacturing complexity when the phase number becomes larger. Therefore, improving the design of multi-phase integrated inductors can help to improve the performance of multi-phase converters and other components.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily drawn to scale, with emphasis instead being placed upon clearly illustrating the principles of the disclosure. In the drawings, like reference numerals designate corresponding parts throughout the several views.

[0004] FIG. **1** illustrates an example of a multi-phase integrated coupled inductor, as well as a graph that compares single-via lateral flux structure to a three-via lateral flux structure, according to embodiments of the present disclosure.

[0005] FIG. **2** illustrates another example of a multi-phase integrated coupled inductor with a slotted core, as well as a graph of AC and DC flux, according to embodiments of the present disclosure.

[0006] FIG. **3** illustrates another example of a multi-phase integrated coupled inductor with a slotted core, according to embodiments of the present disclosure.

[0007] FIG. **4** illustrates examples of multi-phase integrated coupled inductors with slotted cores and vias outside the core, according to embodiments of the present disclosure.

[0008] FIG. **5** illustrates graphs of parameters of various inductor structures along with a diagram of a coupled inductor structure, according to embodiments of the present disclosure.

[0009] FIG. **6** illustrates another example of a multi-phase integrated coupled inductor with a slotted core, according to embodiments of the present disclosure.

[0010] FIG. **7** illustrates another example of a multi-phase integrated coupled inductor with a slotted core, according to embodiments of the present disclosure.

[0011] FIG. **8** illustrates an example of an integrated circuit that includes a multi-phase integrated coupled inductor, according to embodiments of the present disclosure.

DETAILED DESCRIPTION

[0012] The present disclosure relates to multi-phase integrated coupled inductor structures. Compared with a discrete inductor for each buck converter, for example, a multi-phase inductor integrated into one magnetic core can improve power density of multi-phase buck converters and simplify the fabrication and assembly process of the magnetic core and buck converters. The embodiments described herein are not limited to use with buck converters, however, as the concepts can be applied to improve the performance of other converter topologies.

[0013] Compared with a non-coupled inductor, a negative coupled inductor can realize small current ripple and fast transient speed at the same time, which is preferred from a circuit performance point of view. On the other hand, negative coupling can help reduce the DC flux or flux density in the magnetic core. Therefore, higher inductor current can be applied without magnetic core saturation. As the development of CPUs and GPUs in digital devices continuously grows, the power demand of digital devices is becoming higher and higher. As a result, more phases can be added to meet high power demand. Meanwhile, a small inductor size and a low profile are becoming more and more critical for inductor design, due to the limited space in digital devices.

[0014] Negative coupled inductors can include pieces of magnetic core, and each magnetic piece can wrap two conductors. Each phase inductor can be negatively coupled to another two inductors. While negative coupling can help to reduce DC flux in the magnetic core, existing structures can require one piece of magnetic core for each phase, which increases manufacturing complexity when the phase number becomes larger. In addition, some structures that include core slots can utilize a low permeability material in the slot.

[0015] While these structures can increase steady-state inductance while maintaining relatively low transient inductance, these structures can be complex and expensive to manufacture. Therefore, improving the design of multi-phase integrated inductors can help to improve the performance of multi-phase converters and other components. The present disclosure describes multi-phase integrated coupled inductor structures that provide a compact form factor using any odd number of vias larger than one in each inductor. These structures can provide a good ratio of steady-state inductance to transient inductance without using a low permeability material within the slots.

[0016] The structures described herein include multi-phase integrated coupled inductor structures. One aspect of the multi-phase integrated coupled inductor structures can include coupled inductors, where each inductor includes an asymmetrical arrangement of vias in two lines or columns of parallel vias. The lines or columns are parallel as they pass through a magnetic core in one example. In some examples, the lines can correspond to two symmetrical or same-length (including width and depth) open air core slots in the magnetic core. In other words, an inductor can have a different number of vias in each open air core slot.

[0017] A single slot can have a different number of vias from a first inductor than it has from a second inductor that is coupled to the first inductor. For two-phase coupled inductor structures, the positions or arrangement of the vias in the magnetic core can enable coupling between two inductors to be controlled by design without increasing the inductor footprint or adding an exta low permeability magnetic material.

[0018] Multi-phase integrated coupled inductor structures of any even number of phases are also proposed. By utilizing flux cancellation caused by phase shifting in multi-phase buck converters and adding extra slots to strengthen flux interaction between multi-phase inductors, smaller core loss and smaller inductor size can be achieved in the structures described herein. The structures can be applied to many portable electronic devices such as laptops, desktops, smartphones, as well as other consumer, industrial, and other electronic devices. The structures can be designed to fit within a footprint of a processor chip of the electronic device.

[0019] In one example, a multi-phase integrated coupled inductor system includes a coupled set of inductors integrated in a magnetic core. A first inductor of the coupled set of inductors includes a first plurality of conductive vias that extend through the magnetic core in two symmetrical core slots. The first plurality of conductive vias can be asymmetrically distributed in the two symmetrical core slots. A second inductor of the coupled set of inductors includes a second plurality of conductive vias that extend through the magnetic core in the two symmetrical core slots. The second plurality of conductive vias are asymmetrically distributed in the two symmetrical core slots. The coupled inductor system also includes a control circuit that controls at least one switch for the first inductor according to a first phase, and controls at least one switch for the second inductor according to a second phase. Other multi-phase integrated coupled inductors and inductor systems are described.

[0020] Turning to the drawings, FIG. **1** illustrates an example of a multi-phase integrated coupled inductor structure **100**. The multi-phase integrated coupled inductor structure **100** is provided as one representative example to convey the concepts described herein. Other coupled inductor structures are described below with reference to other figures. The coupled inductor structure **100** can be used in a power converter, including a DC-DC step-down converter, such as a buck converter, although it is not limited to use in any particular topology of converter.

[0021] As shown, the multi-phase integrated coupled inductor structure **100** includes an inductor **103** and an inductor **106**. The inductors **103** and **106** include vias, and the inductors **103** and **106** are each three-via structures. A single via lateral flux structure **107** is shown in FIG. **1** to provide a three-dimensional representation of the vias of the multi-phase integrated coupled inductor structure **100**. The flux can be seen to be lateral to the core, since the via runs through the core, rather than along the core, as this can result in vertical inductance.

[0022] A graph **108** in FIG. **1** shows the flux density in a core around the single via lateral flux structure **107**. In the example shown, the example can have a 2×2 mm footprint, 0.5 mm thickness and 0.15 mm radius for the via. High AC flux density can be seen in the core, which can cause significant core loss for the single via lateral flux structure **107** when used alone. A lateral flux structure or component can generate flux that is lateral, or parallel to the two opposite and largest surface area faces of the magnetic core, and parallel to a main board of a device that the lateral flux structure is a component of.

[0023] The three-via structure of each of the inductors **103** and **106** can reduce AC flux density in the core individually in comparison with the single via structure, as can be seen in the right side of the graph **108**. In this example, the footprint and the thickness are kept the same for new structures. The combination of these structures can provide further benefit when formed and controlled as the multi-phase integrated coupled inductor structure **100**.

[0024] The inductors **103** and **106** can be coupled inductor structures with a single magnetic core **109**. For the vias, a black cross and a black dot represent current direction flowing into and out of the image, respectively. The inductor **103** includes vias **112**, **115**, and **118**. As can be seen, the inductor **103** can include an asymmetrical arrangement of vias in two lines or columns from an overhead view.

[0025] The arrangement of vias **112**, **115**, and **118** of the inductor **103** can be referred to as asymmetric based on having a different number of vias in each of the two columns, such as two vias in the left column and one via in the right column. The inductor **106** includes vias **121**, **124**, and **127**. As can be seen, the inductor **106** can also include an asymmetrical arrangement of vias in two lines or columns from an overhead view. The inductor **106** can also have a different number of vias in each of the two columns, such as one via in the left column and two vias in the right column.

[0026] Current flow through the inductor **103** can through a conductive path from a near side of the core **109** (i.e., the top of the sheet of FIG. **1**), through the via **112** into the image towards an opposite far side of the core **109**; over to the via **115** across a conductor on the far side of the core **109** as represented by the dashed line; up through the via **115** towards the near side of the core **109**; over to the via **118** on a conductor on the near side of the core **109**; and down through the via **118** into the image towards the far side of the core **109**. Current can flow in either direction along the path as can be understood. The conductor can include any appropriate conductor, including a printed circuit board trace on a circuit board, an insulated conductor, a magnet wire, or another conductor.

[0027] In some cases, the distance to the edge of the core **109** from a via can be g_1, while g_2 is a lateral distance between vias. In some examples, the ratio of $g_1:g_2$ can be 2. However, the AC flux density is weaker in the middle area of the core **109**, so the overall footprint of the multi-phase integrated coupled inductor structure **100** can be further reduced by reducing the distance g_2, for example, so that the ratio of $g_1:g_2$ is 1.5. In other cases, g_2 can be selected to reduce the distance to achieve a particular or predetermined maximum amount of inductor loss, such as no difference (i.e., 0%), 1%, 2%, 3%, 4%, 5%, or another threshold amount.

[0028] Current flow through the inductor **106** can flow through a conductive path from a near side of the core **109** through the via **121** into the image towards an opposite far side of the core **109**; over to the via **124** across a conductor on the far side of the core **109** as represented by the dashed line; up through the via **124** towards the near side of the core

109; over to the via **127** across a conductor on the near side of the core **109**; and down through the via **127** into the image towards the far side of the core **109**.

[0029] The example multi-phase negatively coupled integrated inductor structure **100** shown in FIG. **1** includes two phases of coupled three-via inductors. However, any odd number of vias larger than one can be used for each inductor in other integrated inductor structures, and any even number of phases can be used in other integrated inductor structures. Therefore, the distance between two inductors, identified as d_1, can be small, and adding low permeability magnetic material is no longer needed to keep the coupling coefficient lower than one. This also simplifies the fabrication complexity of the magnetic core, and enables the inductor footprint to be smaller compared with existing structures.

[0030] FIG. **2** shows an example of a multi-phase integrated coupled inductor structure **200**, as well as a graph **202** of the DC and AC magnetic flux densities in the inductor structure **200**. The multi-phase integrated coupled inductor structure **200** is provided as one representative example to convey the concepts described herein. The coupled inductor structure **200** can be used in a power converter, including a DC-DC step-down converter, such as a buck converter, although it is not limited to use in any particular topology of converter.

[0031] The multi-phase integrated coupled inductor structure **200** is similar in many respects to the multi-phase integrated coupled inductor structure **100**, except that the multi-phase integrated coupled inductor structure **200** includes the core slots **203** and **206**. The inductor L**1** can include an asymmetrical arrangement of vias in two lines or columns from an overhead view. For the vias of L**1**, a black cross and a black dot represent current direction flowing into and out of the image, respectively. The black flux paths can be symbolic representations of general paths of the magnetic field and flux lines generated using the vias of L**1** for discussion purposes, and are not intended to be exact or scale representations. The arrangement of vias of the inductor L**1** can be referred to as asymmetric based on having a different number of vias in each of the two cores slots **203** and **206**, such as two vias in the left core slot **203** and one via in the right core slot **206**. The core slots **203** and **206** can be parallel and have a substantially similar or identical length, and can be referred to as symmetrical core slots.

[0032] For the vias of L**2**, a white cross and a white dot represent current direction flowing into and out of the image, respectively. The white flux paths can be symbolic representations of general paths of the magnetic field and flux lines generated using the vias of L**2** for discussion purposes, and are not intended to be exact or scale representations. The inductor L**2** can also include an asymmetrical arrangement of vias in two two cores slots **203** and **206** from an overhead view, for example, having one via in the left two cores slot **203** and two vias in the right right core slot **206**.

[0033] Current flow through the inductor L**1** can through a conductive path from the near side of the core a **210** (i.e., the top of the sheet of FIG. **2**), down through the top left via of L**1** into the image towards an opposite far side of the core **210**; over to the top right via of L**1** across a conductor on the far side of the core **210**; up through the top right via towards the near side of the core **210**; over to the bottom left via of L**1** through a conductor on the near side of the core **210**, and down through that bottom left via into the image towards the far side of the core **210**.

[0034] Current flow through the inductor L**2** can flow through a conductive path from a near side of the core **210**, through a bottom right via of L**2** into the image towards an opposite far side of the core **210**, over to the bottom left via across a conductor on the far side of the core **210**, up through the bottom left via up towards the near side of the core **210**, over to the top right via of L**2** across a conductor on the near side of the core **210**, and down through that top right via into the image towards the far side of the core **210**.

[0035] As shown, the multi-phase integrated coupled inductor structure **200** includes the core slots **203** and **206**. The multi-phase integrated coupled inductor structure **200** can otherwise be similar to the multi-phase integrated coupled inductor structure **100**. The magnetic core **201** can guide magnetic fields and flux paths generated using the inductive structures that extend through the magnetic core **201**. The magnetic core **201** can be formed from ferromagnetic materials or ferrimagnetic materials. The addition of a core slots **203** and **206**, which can be open air gaps for the vias through the magnetic core **201** can further reduce AC flux density generated by the vias or other inductive structures that extend through the magnetic core **201**. The magnetic core **201** can include a material with a high magnetic permeability relative to the surrounding air and the slots.

[0036] The core slots **203** and **206** are open air gaps in the magnetic core **201**, and the air gaps or open core slots **203** and **206** can be added into the magnetic core **201** of this multi-phase integrated coupled inductor structure **200** to keep small transient inductance at light load. However, due to this special arrangement of via locations, the maximum coupling coefficient between two inductors is only −0.8. The multi-phase integrated coupled inductor structure **200** can include, for each inductor L_1 and L_2, an asymmetrical arrangement of vias in each of two columns, corresponding to the two symmetrical or same-length open core slots **203** and **206**. The inductor L_1 can include two vias in the left core slot **203** and one via in the right core slot **206**. The inductor L_2 can include one via in the left core slot **203** and two vias in the right core slot **206**.

[0037] For example, one can consider the inductor L_1, and the flux distribution generated by the vias in the left core slot **203**. There can be a clockwise direction flux of phase one corresponding to the inductor L_1 as indicated by the thick black line and arrows on the left side of the core **201**. On the right side of the core **201**, there can be an opposite counterclockwise flux generated by phase one corresponding to the inductor L_1 as indicated by the thin black line and arrows on the right side of the core **201**. Since there is only one via on the right side, the flux is reduced compared to the flux in the left side. The second inductor L_2 generates flux corresponding to the thin white line and arrows on the left and thick white line and arrows on the right side of the core. This can be considered in the mutual induction portion of the analysis, as shown.

[0038] Inductance of the left core and the right core of the core **201** can be considered separately. Take phase 1 as an example, where only phase one corresponding to the inductor L_1 has excitation. For this analysis, first considering the inductance of right core, one can consider flux in the core, and ignore flux in the air slot. Self inductance of L_1 in the right hand side of the core, L_{self1_right}, can be described using equation (1).

$$L_{self1\_right} = N\frac{d\Phi}{di} = \frac{d\Phi_1}{di_1} \triangleq L \quad (1)$$

N can be 1 since there is one via on the right hand side. Mutual inductance in consideration of the right side of **L2**, M_{12_right}, can be described using equation (2), in view of the mutual effect of two vias for L_2 on the right side of the core.

$$M_{12\_right} = -2\frac{d\Phi_1}{di_1} = -2L \quad (2)$$

On the other side, self inductance of L_1 in the left hand side of the core, L_{self1_left}, can be described using equation (3), since there are two vias for L_1 on the left side.

$$L_{self1\_left} = 2\frac{d(2\Phi_1)}{di_1} = 4L \quad (3)$$

Mutual inductance in consideration of the left side of L_1, M_{12_left}, can be described using equation (4), since there is one via for L_2 on the left side of the core.

$$M_{12\_left} = -\frac{d(2\Phi_1)}{di_1} = -2L \quad (4)$$

L_{self1_total} can be can be described using equation (5).

$$L_{self1\_total}=4L+L=5L \quad (5)$$

M_{12_total} can be described using equation (6).

$$M_{12\_total}=-(2L+2L)=-4L \quad (6)$$

The coupling coefficient a can be described using equation (7).

$$\alpha \triangleq \frac{M_{12\_total}}{L_{self1\_total}} = -0.8 \quad (7)$$

[0039] FIG. **3** shows an example multi-phase integrated coupled inductor structure **303**. This shows one way that a multi-phase integrated coupled inductor structure can be expanded or extended to include additional vias, and any odd number of vias through open air slots within a core. For the vias in each inductor in FIG. **3**, a black cross represents current direction flowing into the image, and a black dot represents current direction flowing out of the image. Solid lines can represent conductors on a near side of the magnetic core, while dashed lines can represent conductors across a far side of the magnetic core.

[0040] The multi-phase integrated coupled inductor structure **303** can be considered a "3+2" or "3:2" structure, referring to respective vias in corresponding air gaps, since each of the two coupled inductors has 3 vias in a first open air core slot and 2 vias in a second open air core slot. As can be understood, any "(N)+(N−1)" structure can be constructed, where N is an odd integer, and N−1 corresponds to an integer greater than zero, an integer greater than or equal to one, or a non-zero positive integer. These structures can be an asymmetrical arrangement of vias in two columns, which in some examples can correspond to two symmetrical or same-length open air core slots.

[0041] FIG. **4** shows an example multi-phase integrated coupled inductor structure **403** and an example multi-phase integrated coupled inductor structure **406**. The multi-phase integrated coupled inductor structure **403** shows that some examples can enable a multi-phase integrated coupled inductor structure to include a wide variety of ratios between vias in corresponding air gaps by including vias that are outside of, or unsurrounded by, the core.

[0042] A black cross represents current direction flowing into the image, and a black dot represents current direction flowing out of the image. Solid lines can represent conductors on a near side of the magnetic core, while dashed lines can represent conductors across a far side of the magnetic core. The multi-phase integrated coupled inductor structure **403** can be considered a "3+1" or "3:1" structure.

[0043] The multi-phase integrated coupled inductor structure **406** shows that some examples can enable a multi-phase integrated coupled inductor structure to have connections to a single side of the core by including vias that are outside of the core. For example, the multi-phase integrated coupled inductor structure **406** can be considered a "2+1" or "2:1" structure, which is substantially similar to the multi-phase integrated coupled inductor structure **200** of FIG. **2**. However, in this example, the vias that are outside of the core can enable each inductor of the structure to include a current path that starts and ends on a single side of the core and within a footprint of the processor component, where connections corresponding to the start and the end of the current path are on a single side of the core.

[0044] FIG. **5** shows a set of graphs **503** for coupling coefficient, steady-state inductance, and transient inductance for various structures. Generally, steady state inductance can be described using equation (8).

$$L_{ss} = L_{self}\frac{1-\alpha^2}{1+\alpha\frac{D}{1-D}} \quad (8)$$

[0045] Transient inductance can be described using equation (9).

$$L_{tr}=L_{self}(1+\alpha) \quad (9)$$

[0046] This set of graphs **503** shows that the "2+1," "3+2," and "3+1" structures can provide good performance including a higher steady state inductance than transient inductance for each example, without using a low permeability material within slots.

[0047] FIG. **5** also shows an example diagram **506** and corresponding graph that shows how coupled inductors can be controlled to have a particular switching sequence using a switching controller **510** to achieve a higher steady state inductance than transient inductance. For non-coupled inductors, steady state inductance L_{ss} can be equal to transient inductance L_{tr}. However, when negative coupled inductors are used, steady state inductance L_{ss} can be greater than transient inductance L_{tr}. In the graph, steady state inductance L_{ss} can correspond to L_{eq1}, which can be related to inductor current ripple. Transient inductance L_{tr} can correspond to L_{eq2}, which can be related to transient speed.

[0048] The switching controller **510** or control circuit can be embodied as a power management integrated circuit, for example. The switching controller **510** can control one or more switches for the inductor L_1 according to a first phase, and control one or more switches for the inductor L_2 according to a second phase. If there are more inductors, as shown in FIGS. **6** and **7**, additional phases can be controlled. In some cases, adjacent inductors can be controlled by switching to correspond to different phases. V_1 and V_2 can substantially be controlled by the switches of a branch of a corresponding inductor shown in the diagram **506**.

[0049] The switching controller **510** can be embodied in the form of hardware, firmware, software executable by hardware, or as any combination thereof. If embodied as hardware, the switching controller **510** be implemented as a collection of discrete analog, digital, or mixed analog and digital circuit components. The hardware can include one or more discrete logic circuits, microprocessors, microcontrollers, or digital signal processors (DSPs), application specific integrated circuits (ASICs), programmable logic devices (e.g., field-programmable gate array (FPGAs)), or complex programmable logic devices (CPLDs)), among other types of processing circuitry.

[0050] FIG. **6** shows an example four-phase integrated coupled inductor structure **600** with three vias for each inductor. For the vias in each inductor in FIG. **6**, a black cross represents current direction flowing into the image, and a black dot represents current direction flowing out of the image. Solid lines can represent conductors on a near side of the magnetic core, while dashed lines can represent conductors across a far side of the magnetic core.

[0051] This structure can include strong negative coupling between inductor **603** and inductor **606**, as well as between inductor **609** and inductor **612**. The coupling between any other two inductors can be controlled by controlling the distance d_2 between the structures. In general, the couplings between other sets of inductors can be weaker than the coupling between inductor **603** and inductor **606**, and the coupling between inductor **609** and inductor **612**. In the core area controlled by distance d_2, the flux of all four phases can interact with each other due to magnetic integration. By controlling phase shifting between four phases, the AC flux density can become smaller in this area. Therefore, the core loss of the four-phase inductor structures can be smaller than that of two, two-phase inductor structures. Then inductor size of these four-phase inductor structures can be further reduced by reducing distance d_2. While the four-phase integrated coupled inductor structure **600** appears like two of the multi-phase integrated coupled inductor structures **200** of FIG. **2**, multiple ones of any of the structures described can be adapted for multi-phase structures for any even number of phases.

[0052] FIG. **7** shows an example four-phase integrated coupled inductor structure **700** with three vias for each inductor. For the vias in each inductor in FIG. **6**, a black cross represents current direction flowing into the image, and a black dot represents current direction flowing out of the image. Solid lines can represent conductors on a near side of the magnetic core, while dashed lines can represent conductors across a far side of the magnetic core.

[0053] This structure can include a strong negative coupling between inductor **703** and inductor **706**, as well as between inductor **709** and inductor **712**. The coupling between any other two inductors can be controlled by controlling the distance d_2 between the structures. In general, the couplings between other sets of inductors can be weaker than the coupling between inductor **703** and inductor **706**, and the coupling between inductor **709** and inductor **712**. In the core area controlled by distance d_2, the flux of all four phases can interact with each other due to magnetic integration. And because of phase shifting between four phases, the AC flux density can become smaller in this area. Therefore, the core loss of the four-phase inductor structures can be smaller than that of two, two-phase inductor structures. Then the inductor size of these four-phase inductor structures can be further reduced by reducing distance d_2. While the four-phase integrated coupled inductor structure **700** appears like two of the multi-phase integrated coupled inductor structures **200** of FIG. **2**, multiple ones of any of the structures described can be adapted for multi-phase structures for any even number of phases.

[0054] Furthermore, the four-phase integrated coupled inductor structure **700** can include slots **715** and **718** added between inductor **706** and inductor **709**. In some cases, these slots **715** and **718** can be between two sets of coupled inductors, here a first coupled set corresponds to inductors **703** and **706**, and a second coupled set corresponds to inductors **709** and **712**. All inductors can be considered a set of four coupled inductors of the overall structure, and one or more switching control circuit can control the phases corresponding to each inductor in order to provide the desired characteristics, such as higher steady state inductance compared to transient inductance. The coupling slots **715** and **718** can be thinner than the slots containing the vias, or in other cases one long slot can contain all vias of all four coupled inductors, including two sets of two coupled inductors.

[0055] These coupling slots **715** and **718** can increase the coupling between inductor **703** and inductor **709**, between inductor **706** and inductor **709**, and between inductor **706** and inductor **712**. They create positive coupling between inductor **703** and inductor **709**, and between inductor **706** and inductor **712**, as well as negative coupling between inductor **706** and inductor **709**. In other words, the coupling between adjacent inductors is negative while the coupling between alternate or every-other inductor is positive. The slots can have little impact on coupling between inductor **703** and inductor **706**, between inductor **709** and inductor **712**, and between inductor **703** and inductor **712**. The couplings created by these extra coupling slots are impacted by the width of these slots, which can be named l_g. Due to stronger interaction between all fluxes of four phases and phase shifting, the AC flux density in this structure is reduced compared with that of four-phase structure without extra slots, as shown in the graph **720**. Therefore, this structure can have smaller core loss.

[0056] FIG. **8** shows a device **800** that uses a multi-phase integrated coupled inductor structure. The device **800** can correspond to portable electronic devices such as laptops, desktops, smartphones, as well as other consumer, industrial, and other electronic devices. The device **800** can include a main board **803**, a processor chip **806**, a lateral inductor component **809**, a power management integrated circuit **812**, as well as a number of capacitors and other circuit components **815**. This figure shows that the space savings of the lateral inductor component **809**, having any of the multi-phase integrated coupled inductor structures described, can be designed to fit in a footprint of a processor chip **806**. The structures described can meet the expanding inductance needs of electronic devices while also saving space and providing a thinner structure.

[0057] The processor chip or component **806** can be connected on a first side of the main board **803**, while the lateral inductor component **809**, power management integrated circuit **812**, capacitors and other circuit components **815** are located on an opposite side of the main board **803**. Unlike existing technologies, the lateral-flux structures described enable the lateral inductor component **809** to fit within a footprint of a processor chip **806**, and between the processor chip **806** (and main board **803**) and the power management integrated circuit **812**. In some cases, the main board **803** can be etched away or otherwise indented or cut away, such that the lateral inductor component **809** is fully or partially embedded into the main board **803** or other substrate.

[0058] The switching controller **510** can execute software to perform the control aspects of the embodiments described herein. Any software or program instructions can be embodied in or on any suitable type of non-transitory computer-readable medium for execution. Example computer-readable mediums include any suitable physical (i.e., non-transitory or non-signal) volatile and non-volatile, random and sequential access, read/write and read-only, media, such as hard disk, floppy disk, optical disk, magnetic, semiconductor (e.g., flash, magneto-resistive, etc.), and other memory devices. Further, any component described herein can be implemented and structured in a variety of ways. For example, one or more components can be implemented as a combination of discrete and integrated analog and digital components.

[0059] Also, any functionalities described herein that include software or code instructions can be embodied in any non-transitory computer-readable medium, which can include any one of many physical media such as, for example, magnetic, optical, or semiconductor media. More specific examples of a suitable computer-readable medium would include, but are not limited to, magnetic tapes, magnetic floppy diskettes, magnetic hard drives, memory cards, solid-state drives, USB flash drives, or optical discs. Also, the computer-readable medium can be a random access memory (RAM) including, for example, static random access memory (SRAM) and dynamic random access memory (DRAM), or magnetic random access memory (MRAM). In addition, the computer-readable medium can be a read-only memory (ROM), a programmable read-only memory (PROM), an erasable programmable read-only memory (EPROM), an electrically erasable programmable read-only memory (EEPROM), or other type of memory device.

[0060] Further, any logic or functionality described herein can be implemented and structured in a variety of ways. For example, one or more applications described can be implemented as modules or components of a single application or set of instructions. Further, one or more instructions described herein can be executed in shared or separate computing devices or a combination thereof.

[0061] The above-described examples of the present disclosure are merely possible examples of implementations set forth for a clear understanding of the principles of the disclosure. While aspects and figures are provided for clarity of discussion, it is understood that the concepts described with respect to a particular figure or context can be utilized and combined with the concepts described with respect to the other figures and contexts. These variations and modifications can be made without departing substantially from the principles of the disclosure. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

Therefore, the following is claimed:

1. A multi-phase integrated coupled inductor system comprising:

a coupled set of inductors integrated in a magnetic core;

a first inductor of the coupled set of inductors comprising a first plurality of conductive vias that extend through the magnetic core in two symmetrical core slots, wherein the first plurality of conductive vias are asymmetrically distributed in the two symmetrical core slots;

a second inductor of the coupled set of inductors comprising a second plurality of conductive vias that extend through the magnetic core in the two symmetrical core slots, wherein the second plurality of conductive vias are asymmetrically distributed in the two symmetrical core slots; and

at least one control circuit that controls at least one switch for the first inductor according to a first phase, and controls at least one switch for the second inductor according to a second phase.

2. The multi-phase integrated coupled inductor system of claim **1**, wherein a respective via of the first plurality of conductive vias and the second plurality of conductive vias generates lateral flux in the magnetic core.

3. The multi-phase integrated coupled inductor system of claim **1**, wherein the first plurality of conductive vias are asymmetrically distributed by including a first at least one via in a first core slot and a second at least one via in a second core slot, wherein a first count of the first at least one via is different from a second count of the second at least one via.

4. The multi-phase integrated coupled inductor system of claim **1**, wherein the first inductor further comprises a first at least one external via outside of the magnetic core.

5. The multi-phase integrated coupled inductor system of claim **1**, wherein the magnetic core and a lateral inductor component fits within a footprint of a processor, and a first side of the lateral inductor component is connected to a processor component, and an opposite side of the lateral inductor component is connected to a power management integrated circuit comprising the at least one control circuit.

6. The multi-phase integrated coupled inductor system of claim **1**, further comprising:

a second coupled set of inductors with asymmetrically arranged vias within a second set of two symmetrical core slots; and

a set of two coupling slots between the coupled set of inductors and the second coupled set of inductors, wherein a plurality of coupled inductors of the multi-phase integrated coupled inductor system comprise the coupled set of inductors and the second coupled set of inductors.

7. The multi-phase integrated coupled inductor system of claim **6**, wherein the set of two coupling slots is aligned with the two symmetrical core slots and the second set of two symmetrical core slots.

8. An electronic device comprising:

a power management integrated circuit;

a processor component; and

a multi-phase integrated coupled inductor structure physically located between the power management integrated circuit and the processor component, the multi-phase integrated coupled inductor structure comprising:

a coupled set of inductors, wherein a respective inductor of the coupled set of inductors comprises a plurality of conductive vias asymmetrically distributed in two symmetrical core slots in a magnetic core.

9. The electronic device of claim **8**, wherein the power management integrated circuit controls the respective inductor of the coupled set of inductors according to a corresponding phase of a plurality of phases of the multi-phase integrated coupled inductor structure.

10. The electronic device of claim **8**, wherein the plurality of conductive vias are asymmetrically distributed in the two symmetrical core slots so that a different number of vias are used in one of the two symmetrical core slots compared with another one of the two symmetrical core slots.

11. The electronic device of claim **8**, wherein the multi-phase integrated coupled inductor structure comprises a lateral flux structure that generates lateral flux in the magnetic core.

12. The electronic device of claim **11**, wherein the lateral flux comprises a flux path that is substantially parallel to a largest surface area face of the magnetic core and perpendicular to a respective one of the plurality of conductive vias.

13. The electronic device of claim **8**, wherein the respective inductor further comprises at least one external via outside of the magnetic core.

14. The electronic device of claim **8**, wherein a current path of the respective inductor starts and ends on a single side of the magnetic core within a footprint of the processor component.

15. A multi-phase integrated coupled inductor structure comprising:

a magnetic core; and

a coupled set of inductors, wherein an inductor of the coupled set of inductors comprises a plurality of conductive vias asymmetrically distributed among two core slots in the magnetic core.

16. The multi-phase integrated coupled inductor structure of claim **15**, wherein a respective via of the plurality of conductive vias generates lateral flux in the magnetic core.

17. The multi-phase integrated coupled inductor structure of claim **15**, wherein the plurality of conductive vias are asymmetrically distributed by including a first at least one via in a first core slot and a second at least one via in a second core slot, wherein a first count of the first at least one via is different from a second count of the second at least one via.

18. The multi-phase integrated coupled inductor structure of claim **15**, wherein the inductor further comprises at least one external via outside of the magnetic core.

19. The multi-phase integrated coupled inductor structure of claim **15**, wherein the coupled set of inductors comprises an even number of inductors corresponding to an even number of phases of the multi-phase integrated coupled inductor structure.

20. The multi-phase integrated coupled inductor structure of claim **15**, further comprising a set of two coupling slots between a first coupled pair of the coupled set of inductors and a second coupled pair of the coupled set of inductors.

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