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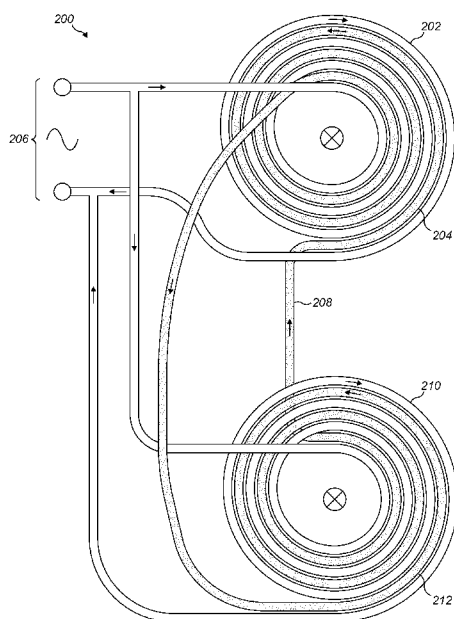


FIG. 2

(57) Abstract: This application relates to an inductive coil assembly that is suitable for use as a wireless charging coil. The inductive coil assembly comprises a first coil configured to receive or output an AC signal, and a second coil forming at least a part of a closed conductive loop which is separate from the first coil. The second coil is interwound with the first coil, with the turns of the second coil disposed between the turns of the first coil, such that the current in the first coil induces a current in the opposite direction in second coil that reduces the proximity effect in the first coil. The inductive coil assembly mitigates the proximity effect without the need for Litz wire arrangements.

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INDUCTIVE COIL ASSEMBLY

TECHNICAL FIELD

This application relates to an inductive coil assembly, and in particular to a Litz-less
5 inductive coil assembly suitable for use as a wireless charging coil.

BACKGROUND ART

One of the major challenges in the high power wireless charging industry is the
increased high frequency losses in the windings at high power. In particular, the proximity
10 effect and skin effect lead to an increase in the effective resistance of the coil at high
frequencies, resulting in losses and generation of heat.

Figure 1 shows an example coil 100 of the prior art which is suitable for use as a
wireless charging coil. The coil is a flat spiral type coil. A pair of these coils are used in wireless
charging applications, with one coil acting as a transmitting coil and the other acting as a
15 receiving coil. An alternating current is input into the transmitting coil, which creates an
alternating magnetic field that induces an alternating current in the receiving coil, thus
transferring power between the coils without a physical wired connection.

However, when an AC current flows in a coil such as that in Figure 1 the effective
resistance of the coil is increased by the proximity effect. The proximity effect arises when the
20 current flowing through a first turn of the coil induces a current in the adjacent turns of the coil.
The induced current causes the current flowing through the adjacent turns to be concentrated
on the sides of the wire furthest from the first turn, termed current crowding. Therefore the
effective cross sections of the adjacent turns are reduced, which increases the effective
resistance of the coil.

25 The increase in the effective resistance due to the proximity effect becomes larger at
higher frequencies. Therefore although the proximity effect is not problematic in low frequency
or DC applications, in high frequency AC applications the increase in effective resistance leads
to unacceptable losses. Losses can typically be twenty to thirty times higher due to the
proximity effect, with over 100W losses at high frequencies. These high losses result in heat
30 generation that can damage or destroy the device.

Approaches have been used to mitigate high frequency losses in interwound
transformer windings. However, these are not applicable to applications where the primary
and secondary windings are mounted physically apart, such as wireless charging applications,
or to single coil applications, such as inductors.

The present solution to this problem in the case of separated primary and second coils is the use of well optimized Litz wire arrangements. However, even the best optimized Litz wire arrangements can have resistance factors of sixteen or higher in a multiple turn wireless charging coil due to the proximity effect. Moreover, such Litz wires are expensive, amounting to as much as 30% of the cost of the total unit, and the process of optimizing the size and geometry of the Litz wires windings is often complicated.

We have appreciated that it would be desirable to provide an inductive coil, suitable for use as a transmitter or receiver coil in wireless charging applications, that mitigates high frequency losses without requiring Litz wire based solutions.

SUMMARY OF THE INVENTION

The invention is defined by the independent claims, to which reference should now be made. Advantageous features are set out in the dependent claims.

According to a first aspect of the present invention, an inductive coil assembly, suitable for use as a wireless charging coil is provided. The inductive coil assembly comprises a first coil configured to receive or output an AC signal, and a second coil forming at least a part of a closed conductive loop which is separate from the first coil. The second coil is interwound with the first coil, with the turns of the second coil disposed between the turns of the first coil, such that the current in the first coil induces a current in the opposite direction in second coil that reduces the proximity effect in the first coil.

The first aspect of the present invention eliminates the requirement for use of Litz wires in wireless charging coils, and makes a significant reduction in the high frequency losses. The associated heat generation is therefore reduced. The invention simplifies the coil design process compared to deriving the optimum Litz wire combination for a particular application. The invention eliminates the power and current limitations in wireless charger design, and eliminates the upper limit of the frequency that a high power wireless charger can practically operate.

In further embodiments, the first coil and second coil may be planar coils, and the first and second coils may be interwound such that both coils extend within the same plane.

When the first coil and second coil are planar coils, the end of the innermost turn of the second coil may be connected to the end of the outermost turn of the second coil to form the closed conductive loop.

Alternatively, the first coil and second coil may be solenoid coils, and the first and second coils may be interwound such that the coils overlap when viewed along the winding axis of the coils.

When the first coil and second coil are solenoid coils, the ends of the second coil may be connected to form the closed conductive loop.

The inductive coil may further comprise a third coil that is connected in parallel with the first coil and has the same winding direction as the first coil, and a fourth coil that is
5 connected in series with the second coil and forms part of the closed conductive loop. The fourth coil may be interwound with the third coil, with the turns of the fourth coil disposed between the turns of the third coil, such that the current in the third coil induces a current in the opposite direction in fourth coil that reduces the proximity effect in the third coil.

The second coil and fourth coil may be connected in series such that the current
10 induced in the second coil by the first coil and the current induced in fourth coil by the third coil flow in the same direction around the closed conductive loop.

The third coil and fourth coil may be planar coils that are interwound such that both extend within the same plane, or the third coil and fourth coil may be solenoidal coils that are interwound such that the coils overlap when viewed along the winding axis of the coils.

The first coil, the second coil, the third coil and the fourth coil may all be planar coils.
15 The end of the innermost turn of the second coil may be connected to the end of the outermost turn of the fourth coil, and the end of the outermost turn of the second coil may be connected to the end of the innermost turn of the fourth coil, to form the closed conductive loop.

The first and second coils may be stacked on top of the third and fourth coils, or the
20 first and second coils may be arranged side by side with the third and fourth coils on a flat surface. In either case, the coils may be positioned such that the magnetic flux produced by each of the first and third coils in same direction.

Each coil that is configured to receive or output the AC signal may have the same number of turns as the respective interwound coil in the closed conductive loop, such that the
25 turns of the two interwound coils alternate.

An insulating material may be disposed between the coil or coils configured to receive or output the AC signal and the coil or coils included in the closed conductive loop.

One or more of the coils may include either round wire windings or flat wire windings.

The inductive coil of the first aspect of the present invention may further comprise a
30 first set of one or more coils that are connected in parallel with the first coil and have the same winding direction as the first coil, and a second set of one or more coils that are connected in series with the second coil and form part of the closed conductive loop. Each of the second set of coils may be interwound with one of the first set of coils, with the turns of each of the second set of coils disposed between the turns of the respective interwound coil of the first set
35 of coils, such that the current in each of the first set of coils induces a current in the opposite

direction in the respective interwound coil of the second set of coils that reduces the proximity effect in the first set of coils.

The inductive coil of the first aspect of the present invention may further comprise an additional coil forming at least part of an additional closed conductive loop which is separate from the first coil and the second coil. The additional coil may be interwound with the first coil, with the turns of the additional coil disposed between the turns of the first coil that the turns of the second coil are not disposed between, such that the current in the first coil induces a current in the opposite direction in the additional coil that reduces the proximity effect in the first coil.

According to a second aspect of the present invention a wireless charger device is provided. The wireless charger device includes the inductive coil assembly of the first aspect of the present invention configured to transmit power to an electronic device.

According to a third aspect of the present invention an electronic device is provided. The electronic device includes the inductive coil assembly of the first aspect of the present invention configured to receive power from a wireless charger device.

The present invention eliminates the need for Litz wires in high power wireless charging coils. Moreover, the invention provides much lower high frequency losses compared to the level of losses that can be achieved with even the best optimized Litz wires arrangements.

Alternatively, the present invention can be used to mitigate high frequency losses in other devices which include inductive coils. For example the inductive coil assembly of the present invention can be used as the coil of an inductor, or as either the primary or secondary coil in a transformer in which the primary and secondary coils are not interwound.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be described in relation to the accompanying drawings, in which:

Figure 1 shows a coil of the prior art;

Figure 2 shows a first embodiment of an inductive coil assembly of the present invention;

Figure 3 shows an alternative embodiment of inductive coil assembly of Figure 2;

Figure 4 shows another embodiment of an inductive coil assembly of the present invention;

Figure 5 shows another embodiment of an inductive coil assembly of the present invention;

Figure 6 shows another embodiment of an inductive coil assembly of the present invention.

Figure 7 shows another embodiment of an inductive coil assembly of the present invention.

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DETAILED DESCRIPTION

This application relates to an inductive coil assembly that is suitable for use as a wireless charging coil. The inductive coil assembly comprises a first coil configured to receive or output an AC signal, and a second coil forming at least a part of a closed
10 conductive loop which is separate from the first coil. The second coil is interwound with the first coil, with the turns of the second coil disposed between the turns of the first coil, such that the current in the first coil induces a current in the opposite direction in second coil that reduces the proximity effect in the first coil. The inductive coil assembly mitigates the proximity effect without the need for Litz wire arrangements.

15 Figure 2 shows a first embodiment of the present invention, which seeks to mitigate the proximity effect without the use of Litz wire. The inductive coil assembly 200 of Figure 2 includes a first coil 202, a second coil 204, a third coil 210 and a fourth coil 212. The first coil 202 and third coil 210 are connected in parallel. The first and third coils 202,210 are flat spiral type coils similar to the coil 100 of Figure 1. The first and third coils 202,210 are connected to
20 an input/output terminal 206. The end of the outermost turn of each of the first and third coils 202,210 is connected to one pin of the input/output terminal 206, and the end of the innermost turn of each of the first and third coils 202,210 is connected to the other pin of the input/output terminal 206.

When the inductive coil assembly 200 is used as a transmitter coil in a wireless
25 charging application, an AC signal is input via the terminal 206 across both the first and third coils 202,210. When the inductive coil assembly is used as a receiver coil in a wireless charging application, an AC signal induced in the first and third coils is output from the terminal 206. The first and third coil 202,210 therefore operate in a similar fashion to the coil 100 of the prior art.

30 However, the inductive coil assembly 200 further includes a closed conductive loop 208. The conductive loop 208 includes the second coil 204 and the fourth coil 212. These components are shaded in Figure 2. The second coil 204 is interwound with the first coil 202 about a common winding axis and in a coplanar fashion, such that both coils extend within the same plane, to form an interwound coil pair. Each turn of the first coil 202 is positioned
35 between two turns of the second coil 204, and each turn of the second coil 204 is positioned

between two turns of the first coil 202. In other words, the first coil 202 and the second coil 204 are combined into a planar, double spiral type coil, with the turns alternating between the first coil 202 and the second coil 204 in a radial direction from the winding axis. The fourth coil 212 is similarly interwound with the third coil 210 in the same plane and about a common winding axis, to form a second interwound coil pair. Each turn of the third coil 210 is positioned between two turns of the fourth coil 212, and each turn of the fourth coil 212 is positioned between two turns of the third coil 210, such that in a radial direction from the winding axis, the turns of the third coil 210 and fourth coil 212 alternate.

The second coil 204 and fourth coil 212 are connected in series to form a closed loop (the conductive loop 208). The end of the innermost turn of the second coil 204 is connected to the end of the outermost turn of the fourth coil 212, and the end of the innermost turn of the fourth coil 212 is connected to the end of the outermost turn of the second coil 204. The second and fourth coils 204,212 are electrically isolated from the first and third coils 202,210. In other words the conductive loop 208 is separate from the first and third coils 202,210. This prevents any electrical shorting from occurring between the first and third coils and the conductive loop, which could cause damage or prevent correct operation of the inductive coil assembly 200. Various forms of insulation may be used between the coils configured to receive or output the AC signal and the coils included in the closed conductive loop, such as insulating coating on the wires, Kapton® tape or the like wrapped around the wires, or cast resin or the like encasing the windings.

In the embodiment of Figure 2, the two interwound coil pairs are arranged side by side on a flat surface. The winding axis of the first and second coils 202,204 is parallel to the winding axis of the third and fourth coils 210,212, and all four coils extend within the same plane. The first and third coils 202,210 are oriented such that when viewed from above or below the planes of the coils, the winding direction is the same. For example, the winding direction of both the first and third coils 202,210 is clockwise in the view shown in Figure 2. This ensures that the magnetic flux produced by the first and third coils is in the same direction (into the page in the embodiment of Figure 2, as shown by the $\otimes$ symbol), as otherwise the flux produced by each coil would cancel with the flux produced by the other coil, and the inductive coil assembly would not be suitable for wireless charging purposes. In other words, the first coil 202 and third coil 210 are connected as parallel aiding inductors.

Alternatively, Figure 3 shows a perspective view of another possible layout for the inductive coil assembly 200. In this embodiment, the first and second coils 202,204 are stacked on top of the third and fourth coils 210,212. The winding axis of the first and second coils may be aligned with the winding axis of the third and fourth coils. Again the winding direction of the first and third coils 202,210 must be in the same direction when viewed along

the winding axis, to ensure that the flux produced by the first and third coils is in the same direction so as not to cancel each other. The arrangement shown in Figure 3 provides a more compact inductive coil assembly. Depending on the required shape and dimensions of the inductive coil assembly for the desired application, either the stacked layout of Figure 3 or side by side layout of Figure 2 may be used to tailor the inductive coil assembly to fit the requirements.

The inductive coil assemblies 200 of Figures 2 and 3 can act as either the transmitting coil or the receiving coil in a wireless charging application. An AC signal is input into the first and third coils 202,210, or output from the first and third coils 202,210. No signal is input to or output from the conductive loop 208. The current in the first and third coils 202,210 induces a current flowing in the opposite direction in the second and fourth coils 204,212. The connections between the second and fourth coil as described above are such that the current induced in the second coil by the first coil and the current induced in fourth coil by the third coil flow in the same direction around the closed conductive loop 208, meaning closed current loop flows around the conductive loop 208. Example current directions are shown by the arrows in Figures 2 and 3.

The proximity effect only arises for adjacent conductors carrying currents in the same direction. Unlike in the prior art coil 100, where adjacent turns of the coil each carry a current flowing in the same direction, the configuration of the inductive coil assembly 200 of Figures 2 and 3, and the inclusion of the conductive loop 208, means that each turn of the first and third coils 202,210 is adjacent to a turn carrying a current in the opposite direction. Namely, the turns of the first and third coil 202,210 each carry a current in the opposite direction to the current in the adjacent turns of the second and fourth coils 204,212. Therefore turns carrying currents in opposite directions are placed in close proximity to each other and turns carrying currents in the same direction are separated from one another. The proximity effect is therefore mitigated, and the high frequency losses and associated heat generation are both reduced significantly.

The current induced in the conductive loop 208 is a closed current loop, and therefore does not result in any power consumption other than the losses due to the internal resistance of the conductive loop 208. In other words, the length of current carrying wire is roughly doubled in the inductive coil assembly 200, compared to the first and third coils 202,210 in isolation without the conductive loop 208. This means that the DC losses due to the internal resistance of the wires are roughly doubled. However, at high frequencies the additional DC losses are easily outweighed by the reduction in high frequency losses due to mitigation of the proximity effect. Thus the inductive coil assembly 200 provides an inductive coil, suitable for wireless charging applications, with superior efficiency when used at high frequencies.

As use of expensive and complex Litz wire arrangements are not required in the inductive coil assembly 200 of Figures 2 and 3, the coil design process is simplified. Instead of Litz wires, round wires or flat (profile) wires may be used in the coils of the present invention. A mixture of flat wire coils and round wire coils may be combined. Typically, thin flat wires are
5 used in high frequency applications in order to help mitigate the losses due to the skin effect. These flat wires must be wide enough to accommodate the flow of the high currents.

Any number of turns can be used in the coils as desired depending on the application. Each coil in an interwound coil pair typically has the same number of turns as the other coil in that interwound pair. In other words, each coil that is configured to receive or output the AC
10 signal has the same number of turns as the respective interwound coil in the closed conductive loop. For example in Figure 2 the first coil 202 has the same number of turns as the second coil 204, and likewise for the third and fourth coils 210,212, such that the turns of the two interwound coils alternate. Having the same number of turns in both the coils in a given interwound coil pair is preferred, as this maximises the reduction in proximity effect by ensuring
15 each turn of one coil is adjacent to turns of the other coil, which are carrying a current in the opposite direction. Having a different number of turns in the coils of an interwound coil pair is possible, however, having less turns in second coil (the coil in the conductive loop) compared to the first coil (the coil configured to receive or output an AC signal) would result in the proximity effect being mitigated to a lesser extent. On the other hand, having more turns in the
20 second coil compared to the first coil would lead to additional DC losses in the extra turns of the second coil whilst providing no additional proximity effect benefit.

Typical devices that require high frequency wireless charging include electric vehicles, drones, or household appliances such as robotic vacuum cleaners or the like. The inductive coil assembly 200 of Figures 2 and 3 may be used as either a power transmitting coil, or a
25 power receiving coil. In other words, one or more of the inductive coil assemblies 200 may be placed inside a wireless charger device, such as charging station, and an AC signal can be input into the first and thirds coils so that the inductive coil assemblies 200 transmit power to a receiving coil. One or more of the inductive coil assemblies 200 may act as said receiving coil, and these may be placed in the electronic device to be charged, such as an electric
30 vehicle. The induced signal in the receiving coil may typically charge a power storage device such as a battery.

The inductive coil assembly 200 of Figures 2 and 3 could also be used in conjunction with conventional coils such as coil 100 of Figure 1. The inductive coil assembly 200 of Figures 2 and 3 could be used as a transmitter coil and a conventional coil, for example a Litz based
35 coil, could act as a receiver coil, or vice versa. In other words the inductive coil assembly 200 of Figures 2 and 3 remains compatible with other conventional coils. However, typically both

the transmitting and receiving devices would include one or more of the inductive coil assembly 200 of Figures 2 and 3, as otherwise the conventional coil may be prone to the detrimental effects of the high losses due to the proximity effect.

The present invention can achieve much lower high frequency losses compared to the level of losses that can be achieved with even the best optimized Litz wire arrangements. Therefore, the present invention eliminates the power and current limitations in wireless charger design, and eliminates the upper limit of the frequency that a high power wireless charger can practically operate. The reduction in losses due to the present invention are most prominent at higher frequencies, and at higher numbers of turns.

Figure 4 shows another embodiment of the present invention. The inductive coil assembly 400 of Figure 4 is the same as the inductive coil assembly 200 of Figure 2, except that a fifth coil 450 and sixth coil 452 are included in this embodiment. The fifth coil 450 is connected to the terminal 406 analogously to the first and third coils of the inductive coil assembly 200 of Figure 2. The fifth coil 450 is therefore connected in parallel to the first and third coils 402, 410. The sixth coil 452 is interwound with the fifth coil 450 in a coplanar fashion about a common winding axis, similar to the interwound coil pairs of the previous embodiments. The sixth coil 452 is incorporated into the closed conductive loop 408 (shaded in Figure 4) such that the end of the innermost turn of the sixth coil 452 is connected to the end of the outermost turn of the fourth coil 412, the end of the outermost turn of the sixth coil 452 is connected to the end of the innermost turn of the second coil 404, and the end of the outermost turn of the second coil 404 is connected to the end of the innermost turn of the fourth coil 412. In other words, the connections between the second, fourth and sixth coil are such that the current induced in the second coil by the first coil, the current induced in fourth coil by the third coil, and the current induced in the sixth coil by the fifth coil all flow in the same direction around the closed conductive loop. Example current directions are shown by the arrows in Figure 4. The inductive coil assembly 400 in this embodiment mitigates the proximity effect in a similar fashion to the inductive coil assembly 200 of Figure 2.

In general, additional coils could continue to be added to the inductive coil assembly 400 analogously to the addition of the fifth and sixth coils in the embodiment of Figure 4. Any number of coils could be connected in parallel to the input/output terminal, with the same number of coils included in the conductive loop, and with each of the parallel coils being interwound with one of the coils connected in the conductive loop. In other words, in some embodiments the inductive coil assembly of Figures 2 and 3 may further include a first set of one or more coils that are connected in parallel with the first coil and have the same winding direction as the first coil, and a second set of one or more coils that are connected in series with the second coil and form part of the closed conductive loop. In this case, each of the

second set of coils is interwound with one of the first set of coils, in a similar fashion to the first and second coils of Figure 2. The coils in the second set of coils are connected to the second coil to from the conductive loop such that the currents induced in the second set of coils by the first set of coils flow in the same direction around the closed conductive loop, thus mitigating the proximity effect as in the previous embodiments.

Many other variations on the shape and configuration of the coils are possible. For example, the principle can be applied to any shape of coils, such as square shaped coils. Although wireless charging coils typically have a planar shape, the principle can also be applied to other coils, such as solenoid coils. The only requirement is that the coils connected to the input/output terminal are capable of being interwound with the coils included in the conductive loop. The type and shape of coil can be chosen to optimise the shape and dimensions of the inductive coil assembly for the required purpose. For example planar coils could be used in applications a where a thinner device is required.

As an example, Figure 5 shows an embodiment of the present invention that includes solenoid coils. The inductive coil assembly 500 of Figure 5 includes a first coil 502, a second coil 504, a third coil 510 and a fourth coil 512. In the inductive coil assembly 500 of Figure 5, the first solenoid coil 502 and the third solenoid coil 510 are connected to an input/output terminal 506. The first coil 502 and third coil 510 are connected in parallel such that a first end of the first coil is connected to a first end of the third coil, and the second end of the first coil is connected to the second end of the third coil. In other words, the first coil 502 and third coil 510 are connected as parallel aiding inductors.

The second solenoid coil 504 is interwound in a double helix type configuration with the first coil 502 about a common winding axis, to form one interwound coil pair. The first and second coils therefore overlap when viewed along the winding axis of the first and second coils. The fourth solenoid coil 512 is interwound in a double helix type configuration with the third coil 510 about a common winding axis, to form a second interwound coil pair. The third and fourth coils therefore overlap when viewed along the winding axis of the third and fourth coils. The second and fourth coils 504,512 are connected in series to form a closed conductive loop 508 (shaded in Figure 5). In particular, the end of the second coil 504 which corresponds to the first end of the first coil 502 is connected to the end of the fourth coil 512 which corresponds to the second end of the third coil 510, and the end of the second coil 504 which corresponds to the second end of the first coil 502 is connected to the end of the fourth coil 512 which corresponds to the first end of the third coil 510.

As with the previous embodiments, the two interwound coil pairs can either be placed next to each other on a surface, or can be stacked on top of each other, provided the magnetic

flux produced by the first and third coils 502,510 is in the same direction. When the interwound coil pairs are stacked on top of each other the winding axes of all of the coils may be aligned.

Similarly to the embodiment of Figure 2, the current in the first and third coils 502,510 induces a current flowing in the opposite direction in the second and fourth coils 504,512. The connections between the second and fourth coil described above are such that the current induced in the second coil by the first coil and the current induced in fourth coil by the third coil flow in the same direction around the closed conductive loop. Example currents are shown by the arrows in Figure 5.

In a regular solenoid coil, the proximity effect occurs between the adjacent windings along the axial direction of the solenoid. In the inductive coil assembly 500 of Figure 5 the windings alternate between the first and second coil, or the third and fourth coil, as you move along the axial direction of the solenoids. Therefore the proximity effect is mitigated as wires carrying currents in the same direction are not placed directly adjacent to each other, but instead the direction of the current alternates as you move down the turns of each interwound coil pair.

The present invention could also be applied to other coil configurations. For example multilayer solenoid coils could be used in the interwound coil pairs. In such an embodiment, each winding of the first or third coil may be surrounded by four windings of the second or fourth coil respectively, and each winding of the second or fourth coil may be surrounded by four windings of the first or third coil respectively.

In some embodiments, a mixture of different coil types could be used, for example planar coils could be used as the first and second coil, and solenoid coils could be used as the third and fourth coils. Various other combinations with multiple coil pairs of multiple different coil types could be imagined. However, the coil type within an interwound coil pair must be the same so that the two coils can be interwound. Moreover, care must be taken to ensure that the magnetic flux produced by each of the coils configured to receive or output and AC signal (the first and third coils) is in the same direction, so that the inductive coil assembly can work effectively as a wireless charging coil.

Turning now to Figure 6, a coil configuration in another embodiment of the present invention is shown. The embodiment of Figure 6 includes a first coil 602 connected to an input/output terminal 606, an a second coil 604 which is interwound with the first coil 602 in a similar fashion to the interwound coil pairs of the previous embodiments. In the embodiment of Figure 6 various coil configurations could again be used, for example solenoid coils could be used, and square shaped coils (in both the planar and solenoidal cases) could also be used. However, unlike the previous embodiments, the embodiment of Figure 6 does not include additional coils in parallel with the first coil 602 or in series with the second coil 604.

Instead in this embodiment, the end of the innermost turn of the second coil 604 is connected to the end of the outermost turn of the second coil 604, such that the second coil forms a closed conductive loop 608 (shaded in Figure 6). The second coil 604 is electrically isolated from the first coil 602. In other words, the conductive loop 608 is separate from the first coil 602.

The embodiment shown in Figure 6 can mitigate the proximity effect via the same mechanism as in the embodiments of Figures 2 to 5. Namely, the current in the first coil 602 induces a current flowing in the opposite direction in the second coil 604, which prevents adjacent turns carrying currents in the same direction, preventing an increase in the effective resistance of the wires due to the proximity effect.

Whilst the embodiments of Figures 2 to 5 including multiple interwound coil pairs work universally, the single coil pair arrangement of Figure 6 may be applied in some cases only. In particular, the single coil pair embodiment is only appropriate when the short circuit voltage of the second coil 604 is similar to the back emf of the primary coil 602. When the short circuit voltage of the second coil is much larger than back emf of the primary coil, the current flowing round the closed conductive loop 608 can become too high, and can damage the device.

However, when the short circuit voltage of the secondary coil 604 is only a few times greater than the back emf of the first coil 602, the excessive current in the conductive loop can be mitigated by a configuration as shown in Figure 7. In the inductive coil assembly 700 of Figure 7, a first coil 702 receives or outputs an AC signal from a terminal 706. A second coil 704 is again interwound with the first coil 702, and the ends of the second coil 704 are connected to form a closed conductive loop 708. However, unlike in the embodiment of Figure 6, the second coil 704 has less turns than the first coil 702, and is disposed between only some of the turns of the first coil 702. An additional coil 794 is interwound with the first coil 702 and disposed between the other turns of the first coil 702 that are not disposed against the turns of the second coil 704. The ends of the additional coil 794 are connected to create an additional closed conductive loop 798, in a similar fashion to the conductive loop 708 containing the second coil 702.

Another way of describing the embodiment of Figure 7 is that the conductive loop 608 in a Figure 6 type embodiment (with additional turns) is broken mid-way round the second coil 604, and is reconnected to form two separate closed conductive loops 708, 798. This means that the short circuit voltages induced in the conductive loop 708 and the additional conductive loop 798 are reduced by roughly a half due to the reduced number of turns in the second coil 704 and the additional coil 794, compared to a Figure 6 type embodiment with one conductive loop 608 including a second coil 604 with double the number of turns. Thus large circulating

currents in the closed conductive loops 708,798 can be avoided in the embodiment of Figure 7.

An embodiment with three conductive loop sections could be used in a case where the short circuit voltage of the second coil in the Figure 6 type embodiment is three times the back emf of the first coil, and so on for four or five sections. The number of sections the conductive loop can be broken into is of course limited by the number of turns in the coils.

The invention characterised by the embodiments of Figures 2 to 7 provides a novel construction for a wireless charging coil arrangement, which eliminates the requirement for use of Litz wires, and makes a significant reduction in the losses. The invention can simplify the coil design process compared to deriving the optimum Litz wire combination for a particular application. The invention eliminates the power and current limitations in wireless charger design, and eliminates the upper limit of the frequency that a high power wireless charger can practically operate.

In testing of a prototype of the embodiment of Figure 2 with 10 turns in each coil, a 2.02A current at a frequency of 507kHz led to a temperature rise of only 29 degrees in the coil assembly. This compares to a 38 degrees temperature rise in a conventional 10 turn coil with at 1.98A current at a frequency of 504kHz. Therefore, the invention resulted in roughly a 10 degrees lower temperature rise than for the same current in a prior art coil, due to the mitigation of the proximity effect.

A theoretical calculation for the example of a four turn coil of the present invention operating at a frequency of 120kHz gave reduction in losses of approximately 60% compared to the equivalent Litz wire arrangement. The advantages of the invention become even more prominent as the number of turns in the windings increases. Therefore, as most of wireless charging coils are made with more than four turns, a reduction in losses of well over 60% of the equivalent Litz wire losses can be expected in real life applications.

The invention can be applied to any type of wireless charging coil. The advantages will become more prominent as the power increases and as the number of turns increases. The principle can be used in any power transmitting application where the transmitting coil and the receiving coils are physically apart.

Alternatively, the concept can be used to mitigate high frequency losses in other devices which include inductive coils. For example, an inductive coil assembly of the present invention can be used as the coil of an inductor. The invention can mitigate losses in high frequency inductors, especially inductors where the high frequency component is a significant part of the total current in the inductor coil. The invention can provide significant advantages in high frequency high power inductors, and will make a considerable change to the design approaches of high frequency inductors. Moreover, inductive coil assemblies of the present

invention may be used as either the primary or secondary coil in a transformer in which the primary and secondary coils are not interwound, in order to mitigate high frequency losses in the transformer windings.

Throughout this application references to the conductive loop and closed conductive
5 loop are intended to refer to a closed conductive loop of wire. In other words the closed conductive loop is formed from a single continuous piece of wire with its ends connected together (shorted) into a closed loop. The closed conductive loop of wire is wound to form coiled sections included within the closed conductive loop, for example the second and fourth coils 204,212, or the second fourth and sixth coils 404,412,452, or the second and fourth coils
10 504,512, or the second coil 604, or the second coil 704. The closed conductive loop of wire contains no circuit components within the closed wire loop. A non-zero current is induced in the closed conductive loop and flows round the closed loop of wire to mitigate the proximity effect. The same is true of the additional closed conductive loop 798.

The number of turns pictured in the coils of each of Figures 2 to 7 is for exemplary
15 purposes only, and the coils can have any number of turns, as would be understood by the skilled person. The interconnecting wires shown in Figures 2 to 7 between the different coils and between the coils and the input/output terminals have been spatially arranged for clarity and illustrative purposes. The exact paths of the interconnecting wires are not intended to be limited to such arrangements, and the wires between the different coils and between the coils
20 and the input/output terminals may be arranged in various alternative layouts.

As discussed, the coils in the interwound coil pairs of the described embodiments typically share a common winding axis. However, as would be understood by skilled person, a small offset between the winding axes of the two coils of an interwound coil pair is acceptable provided that the turns of the coils in the interwound coil pair remain disposed between the
25 turns of the other coil, so as to mitigate the proximity effect.

Although described separately, the features of the embodiments outlined above may be combined in different ways where appropriate. Various modifications to the embodiments described above are possible and will occur to those skilled in the art without departing from the scope of the invention which is defined by the following claims.

CLAIMS

1. An inductive coil assembly, suitable for use as a wireless charging coil,
comprising:
 - 5 a first coil configured to receive or output an AC signal; and
 - a second coil forming at least a part of a closed conductive loop which is
separate from the first coil;
wherein the second coil is interwound with the first coil, with the turns of the
second coil disposed between the turns of the first coil, such that the current in the
10 first coil induces a current in the opposite direction in the second coil that reduces
the proximity effect in the first coil.
2. The inductive coil assembly of claim 1, wherein the first coil and second coil are
planar coils, and the first and second coils are interwound such that both coils
15 extend within the same plane.
3. The inductive coil assembly of claim 2, wherein the end of the innermost turn of
the second coil is connected to the end of the outermost turn of the second coil to
form the closed conductive loop.
20
4. The inductive coil assembly of claim 1, wherein the first coil and second coil are
solenoid coils, and the first and second coils are interwound such that the coils
overlap when viewed along the winding axis of the coils.
- 25 5. The inductive coil assembly of claim 4, wherein the ends of the second coil are
connected to form the closed conductive loop.
6. The inductive coil assembly of claims 1, 2 or 4 further comprising:
 - 30 a third coil that is connected in parallel with the first coil and has the same
winding direction as the first coil; and
 - a fourth coil that is connected in series with the second coil and forms part of
the closed conductive loop;
wherein the fourth coil is interwound with the third coil, with the turns of the
fourth coil disposed between the turns of the third coil, such that the current in the
35 third coil induces a current in the opposite direction in fourth coil that reduces the
proximity effect in the third coil.

7. The inductive coil assembly of claim 6, wherein the second coil and fourth coil are connected in series such that the current induced in the second coil by the first coil and the current induced in fourth coil by the third coil flow in the same direction around the closed conductive loop.
8. The inductive coil assembly of claims 6 or 7, wherein either:
the third coil and fourth coil are planar coils that are interwound such that both extend within the same plane, or
the third coil and fourth coil are solenoidal coils that are interwound such that the coils overlap when viewed along the winding axis of the coils.
9. The inductive coil assembly of claims 6 or 7, wherein:
the first coil, the second coil, the third coil and the fourth coil are all planar coils; and
the end of the innermost turn of the second coil is connected to the end of the outermost turn of the fourth coil, and the end of the outermost turn of the second coil is connected to the end of the innermost turn of the fourth coil, to form the closed conductive loop.
10. The inductive coil assembly of any of claims 6 to 9, wherein either:
the first and second coils are stacked on top of the third and fourth coils; or
the first and second coils are arranged side by side with the third and fourth coils on a flat surface;
and in either case, the coils are positioned such that the magnetic flux produced by each of the first and third coils in same direction.
11. The inductive coil assembly of any preceding claim, wherein each coil that is configured to receive or output the AC signal has the same number of turns as the respective interwound coil in the closed conductive loop, such that the turns of the two interwound coils alternate.
12. The inductive coil assembly of any preceding claim, wherein an insulating material is disposed between the coil or coils configured to receive or output the AC signal and the coil or coils included in the closed conductive loop.

13. The inductive coil assembly of any preceding claim, wherein one or more of the coils include either round wire windings or flat wire windings.

14. The inductive coil assembly of claim 1 further comprising:

5 a first set of one or more coils that are connected in parallel with the first coil and have the same winding direction as the first coil; and

 a second set of one or more coils that are connected in series with the second coil and form part of the closed conductive loop;

10 wherein each of the second set of coils is interwound with one of the first set of coils, with the turns of each of the second set of coils disposed between the turns of the respective interwound coil of the first set of coils, such that the current in each of the first set of coils induces a current in the opposite direction in the respective interwound coil of the second set of coils that reduces the proximity effect in the first set of coils.

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15. The inductive coil of any of claims 1 to 5, further comprising:

 an additional coil forming at least part of an additional closed conductive loop which is separate from the first coil and the second coil;

20 wherein the additional coil is interwound with the first coil, with the turns of the additional coil disposed between the turns of the first coil that the turns of the second coil are not disposed between, such that the current in the first coil induces a current in the opposite direction in the additional coil that reduces the proximity effect in the first coil.

25 16. A wireless charger device including the inductive coil assembly of any of claims 1 to 15, wherein the inductive coil assembly is configured to transmit power to an electronic device.

30 17. An electronic device including the inductive coil assembly of any of claims 1 to 15, wherein the inductive coil assembly is configured to receive power from a wireless charger device.

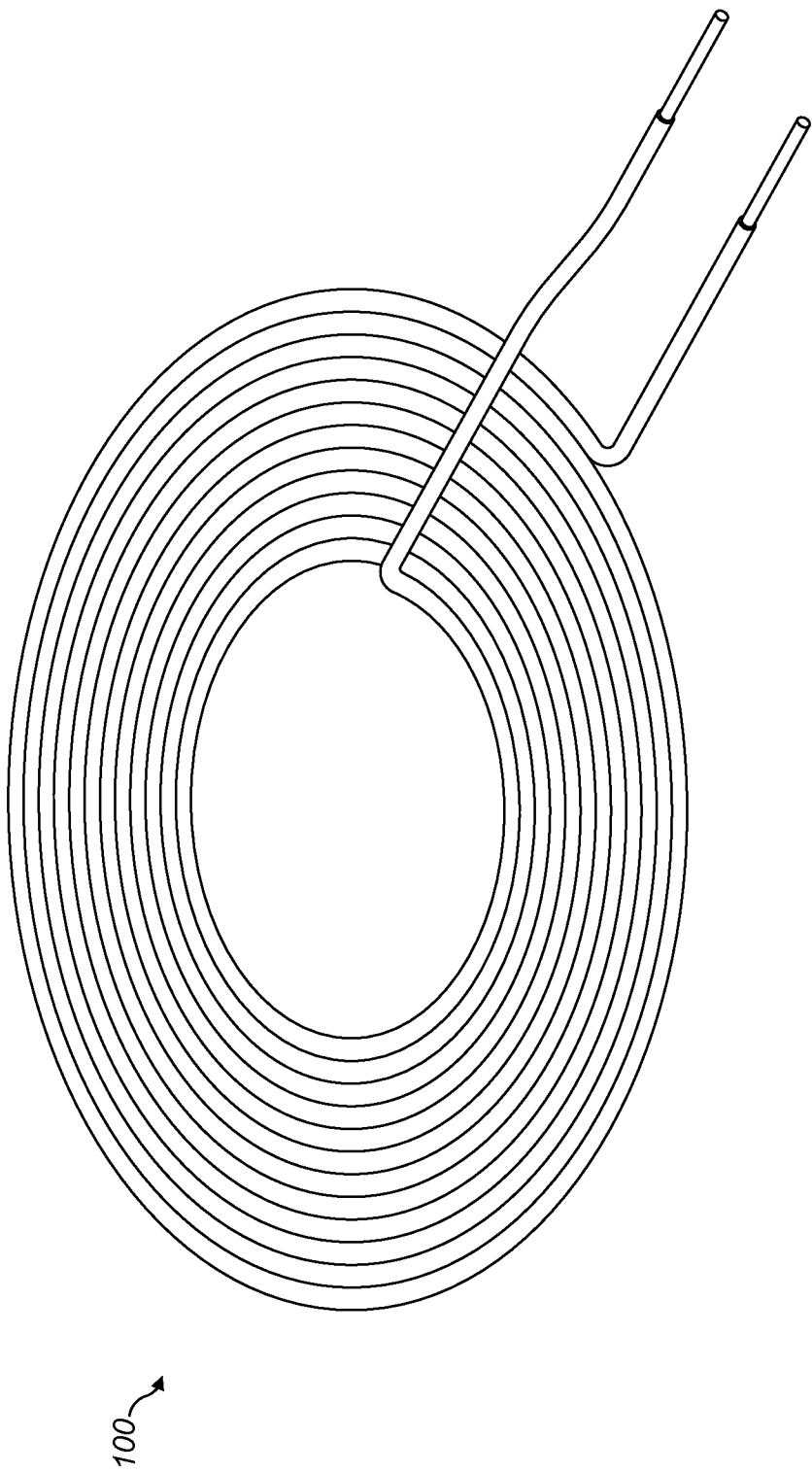


FIG. 1
(Prior Art)

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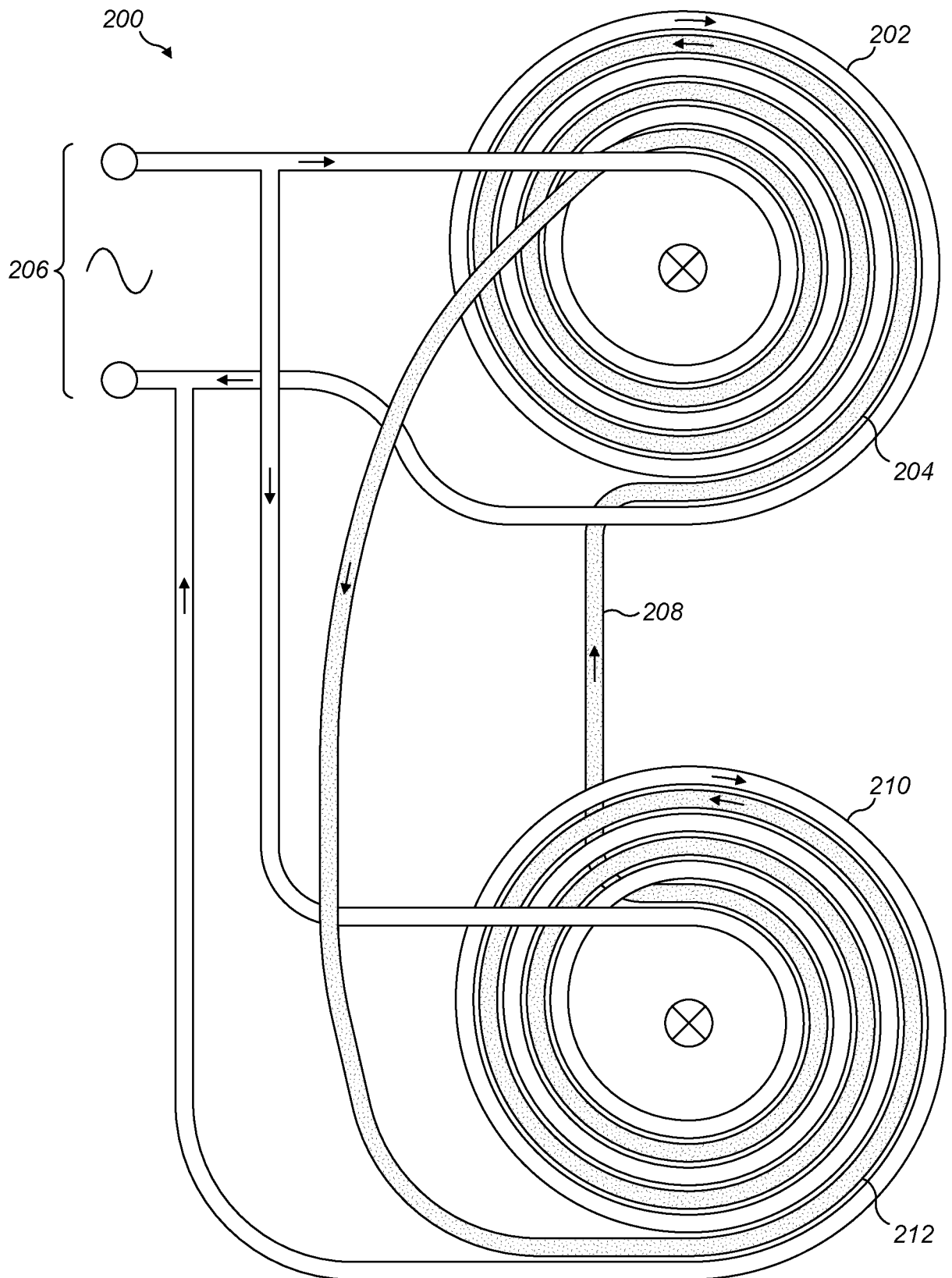


FIG. 2

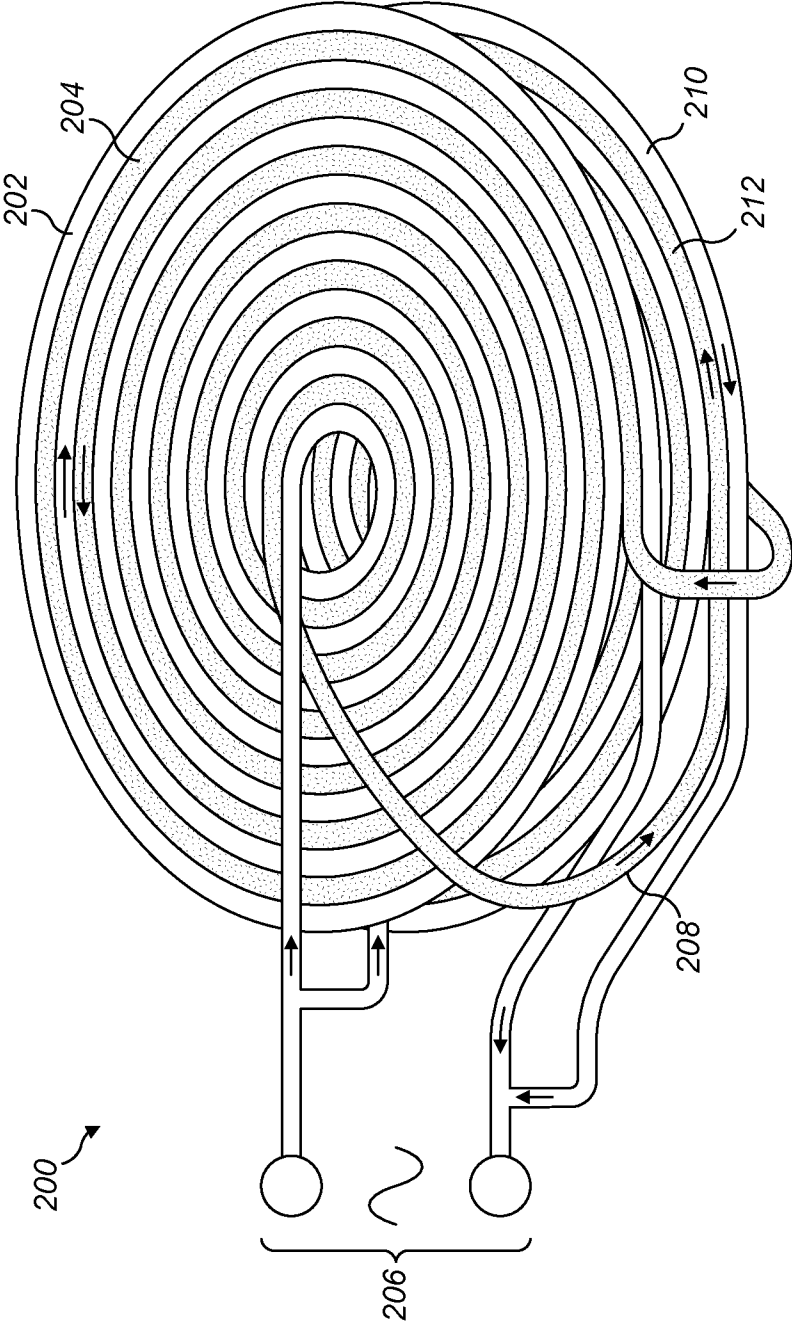


FIG. 3

4 / 7

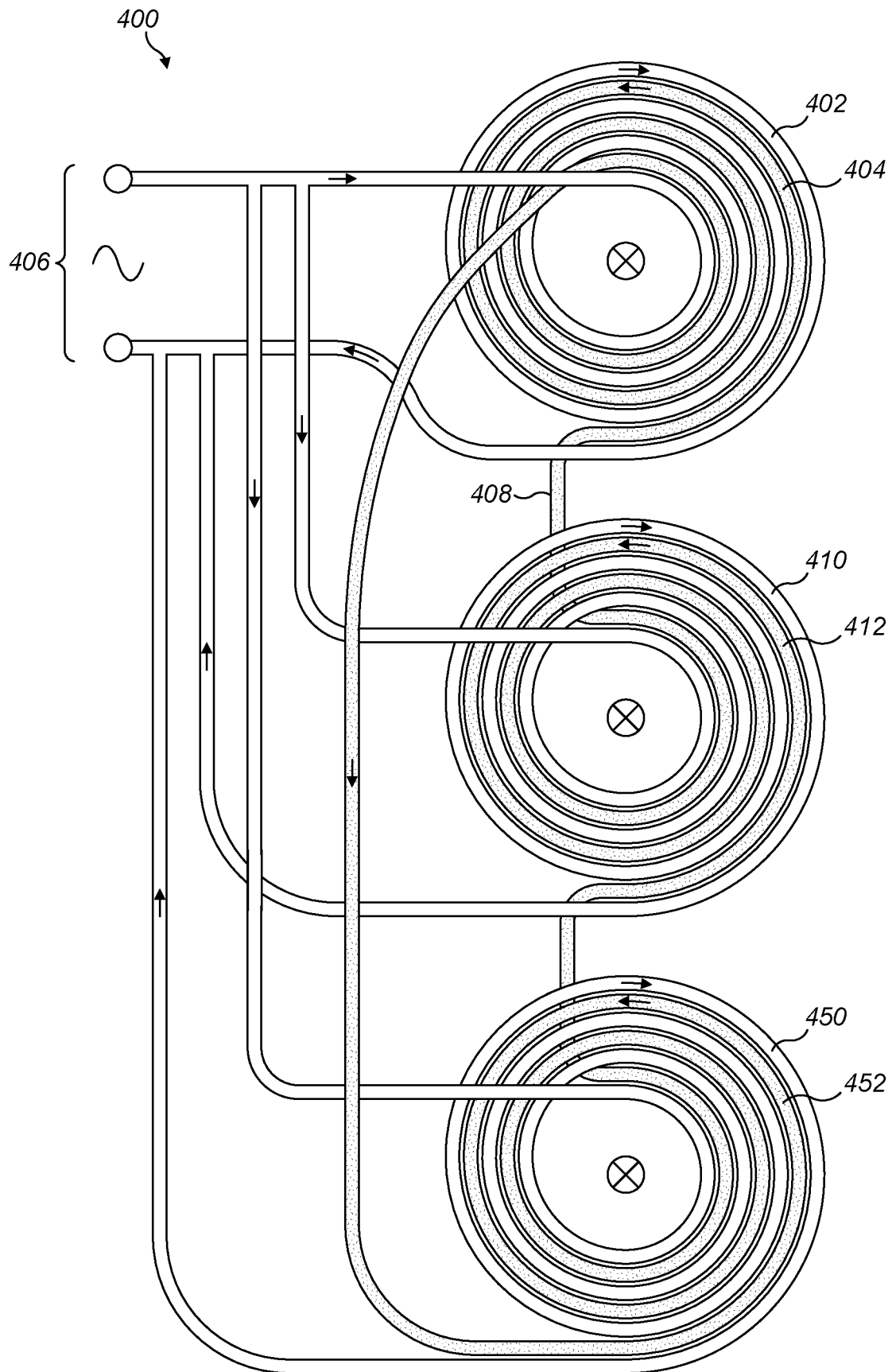


FIG. 4

5 / 7

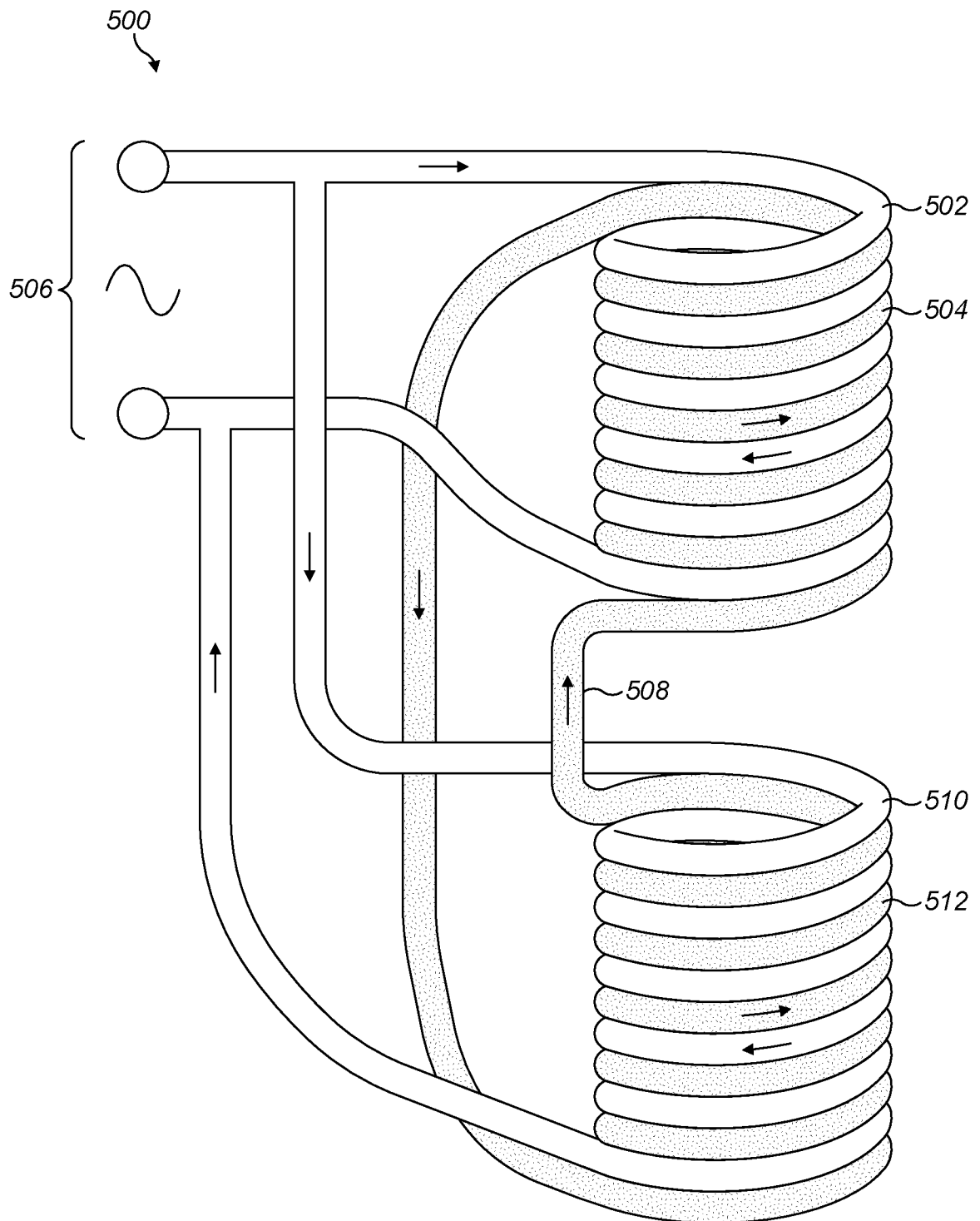


FIG. 5

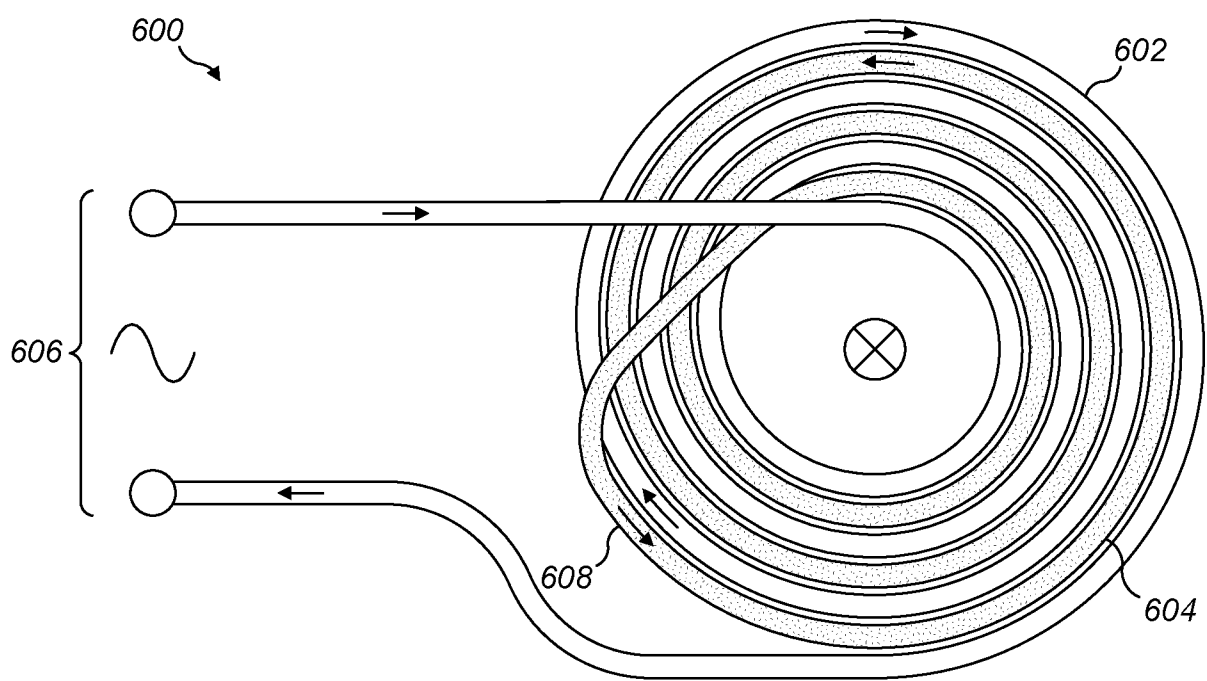


FIG. 6

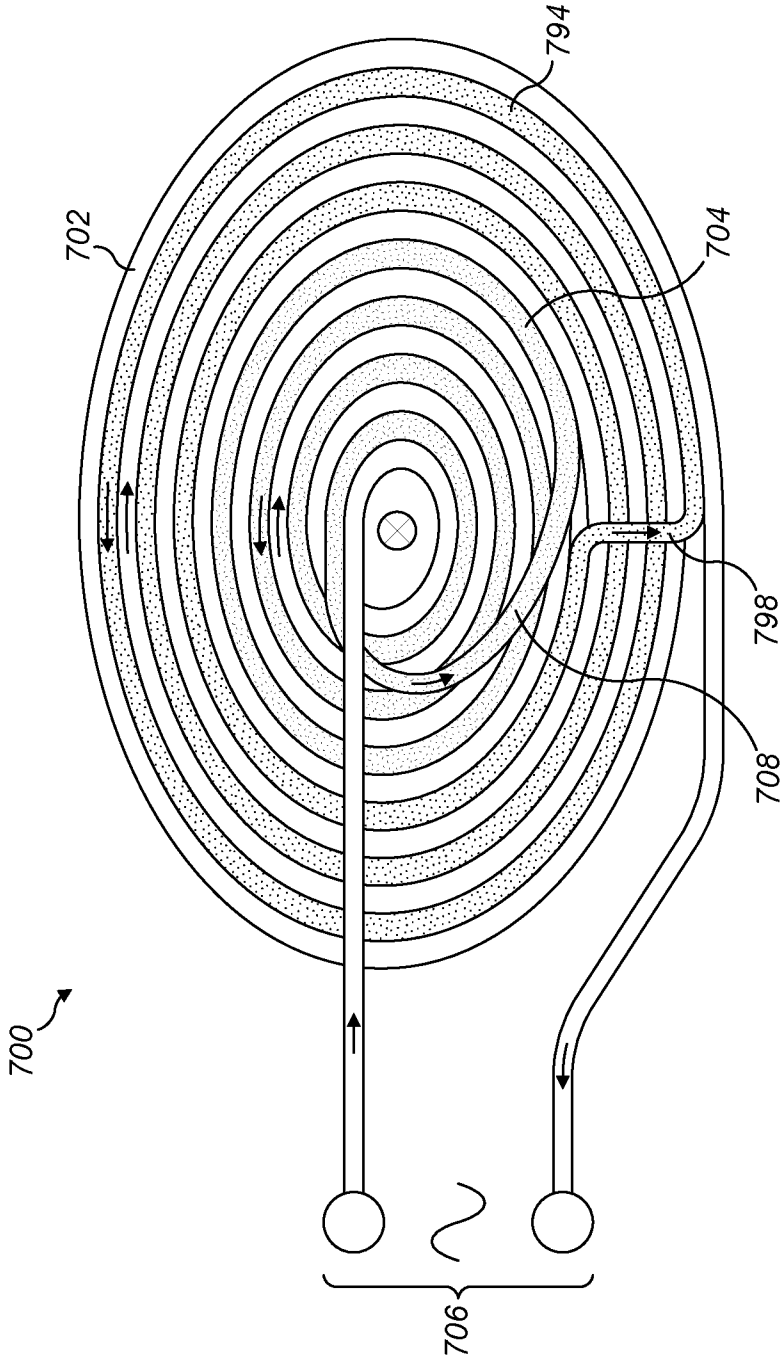


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2021/051885

A. CLASSIFICATION OF SUBJECT MATTER INV. H01F27/28 H01F27/38 H01F38/14 H02J50/10 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H01F H02J		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A A A	US 2020/200937 A1 (WIDMER HANS PETER [CH] ET AL) 25 June 2020 (2020-06-25) 48, 65, 113, 114, 121, 128, 159 - 161, 165 - 167; figures 1, 2B, 5A, 5H, 9 ----- US 2020/203994 A1 (CHO IN KUI [KR] ET AL) 25 June 2020 (2020-06-25) 46- 50, 57- 60 and 70; figure 2 and 6 ----- US 2013/187474 A1 (DE BOODT SEBASTIAAN [BE]) 25 July 2013 (2013-07-25) 47- 50 and 52; figures 3, 4a, 4d -----	1-14, 16, 17 15 15 15
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 19 October 2021		Date of mailing of the international search report 05/11/2021
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Brächer, Thomas

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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