



(51) International Patent Classification:
H01F 38/00 (2006.01)

(21) International Application Number:
PCT/US2014/017505

(22) International Filing Date:
20 February 2014 (20.02.2014)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/782,637 14 March 2013 (14.03.2013) US
13/956,374 1 August 2013 (01.08.2013) US
14/181,731 17 February 2014 (17.02.2014) US

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(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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

Published:

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

(54) Title: DUAL-MODE WIRELESS POWER RECEIVER

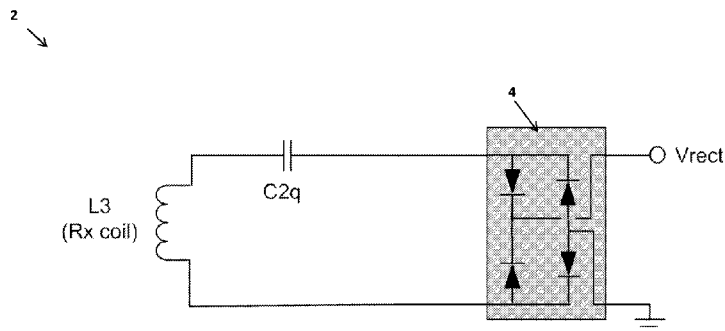


FIG. 1

(57) Abstract: A dual -mode receiver is provided that includes an electromagnetic resonator having one or more inductive elements that are arranged to form a receiver coil and a network of passive components arranged to form a matching network.

Title

DUAL-MODE WIRELESS POWER RECEIVER

Background of the Invention

[0001] The invention is related to the field of wireless power transfer, and in particular to a dual-mode wireless power receiver.

[0002] Wireless power (WP) transfer systems use the mutual inductance between two magnetic coils to transfer power through magnetic induction. These systems are commonly classified as either "inductive" or "resonant". In a purely inductive wireless power transfer system, the source coil, which functions as the primary winding of a transformer, is driven by a voltage or current source. The receive coil, which functions as the secondary winding, is connected to a bridge rectifier, either directly or through an ac-coupling capacitor. The voltages and currents in the two windings can be determined by the relations commonly used to describe transformers.

[0003] In a resonant wireless power transfer system, the source and receiver coils are connected to capacitors to form electrical resonators. From a circuit-design standpoint, the function of the capacitors is to cancel some of the reactive impedance of the inductors, allowing more power to be transferred at a given voltage. The impedance of the inductors and capacitors varies in opposite directions with operating frequency, so the cancellation is only effective over a small range of frequencies. In other words, resonant wireless power systems utilize circuits tuned to a specific frequency at which power is to be transferred. They typically do not allow power transfer at other frequencies.

[0004] In recent years, two wireless power standards have started to emerge. The Wireless Power Consortium has released the Qi standard, which is commonly classified as an inductive charging standard. Although a resonant capacitor is used, the quality factor Q used in the Qi standard is in the low single-digits, implying that resonance is not being substantially leveraged. Devices complying with the Qi standard transmit power in the frequency range of 110-205 kHz. Qi devices typically require relatively close alignment of the source

and receiver coils.

[0005] More recently, several organizations have started to introduce wireless power systems that make use of high quality factor resonant circuits to increase the usable range over which charging can occur. The frequencies used are typically much higher than those used in inductive chargers, largely due to the fact that quality factor of an inductor is proportional to frequency. One proposal for the emerging standard for resonant wireless power recommends an operating frequency in the ISM band at 6.78 MHz.

Summary of the Invention

[0006] According to one aspect of the invention, there is provided a dual-mode receiver. The dual-mode receiver includes an electromagnetic resonator having one or more inductive elements that are arranged to form a receiver coil and a network of passive components arranged to form a matching network. The electromagnetic resonator includes a first selective frequency defined in a low frequency range and a second selective frequency defined in a high frequency range allowing for a rectification circuit to operate in both the high frequency range and low frequency range making maximum use of active circuits.

[0007] According to another aspect of the invention, there is provided a wireless receiver. The wireless receiver includes an electromagnetic resonator having one or more inductive elements that are arranged to form a receiver coil and a network of passive components arranged to form a matching network. The electromagnetic resonator includes a first selective frequency defined in a low frequency range and a second selective frequency defined in a high frequency range allowing for a rectification circuit to operate in both the high frequency range and low frequency range making maximum use of active circuits.

[0008] According to another aspect of the invention, there is provided a method of performing the operations of a wireless receiver. The method includes arranging an electromagnetic resonator to include one or more inductive elements that are arranged to form a receiver

coil and a network of passive components arranged to form a matching network. Moreover, the method includes providing the electromagnetic resonator having a first selective frequency defined in a low frequency range and a second selective frequency defined in a high frequency range allowing for a rectification circuit to operate in both the high frequency range and low frequency range making maximum use of active circuits.

Brief Description of the Drawings

[0009] FIG. 1 is a schematic diagram illustrating an applications circuit that implements a low-Q, inductive charging receiver.

[0010] FIG. 2 is a schematic diagram illustrating a second applications circuit used in accordance with the invention that implements a high-Q resonant wireless power receiver.

[0011] FIG. 3 is a schematic diagram illustrating the circuit topology of the inventive dual-mode receiver.

[0012] FIG. 4 is a schematic diagram illustrating load modulation being implemented through the use of switched capacitors C_c in accordance with the invention.

[0013] FIG. 5 is a schematic diagram illustrating a coil arrangement used in accordance with the invention.

[0014] FIG. 6 is a schematic diagram illustrating an embodiment of the invention that includes a synchronous rectifier.

Detailed Description

[0015] This invention involves the design of a dual-mode wireless power receiver. The dual-mode wireless power receiver can receive power from either an inductive charger operating in the range of hundreds of kHz or a resonant charger operating at a frequency in the MHz range. The dual-mode wireless power receiver can have a low-frequency operating range of 110-205 kHz and a high operation frequency of 6.78 MHz, but the invention can generally be used for any two frequency bands separated by a factor of at least 5.

[0016] FIG. 1 is a schematic diagram illustrating an inductive wireless power receiver circuit 2 that implements a low-Q, inductive

charging receiver. An inductor L3 represents the receiver coil (Rx coil), which is coupled to a source coil. AC power induced in L3 is rectified by a bridge rectifier 4 to generate a dc voltage Vrect. The bridge rectifier 4 is an arrangement of four (or more) diodes in a bridge circuit configuration that provides the same polarity of output for either polarity of input. A bridge rectifier provides full-wave rectification from a two-wire AC input, resulting in lower cost and weight as compared to a rectifier with a 3-wire input from a transformer with a center-tapped secondary winding. Capacitor C2q and inductor L3 form an electromagnetic resonator with a resonant frequency around the wireless power operating frequency. This frequency is typically in the range of hundreds of kHz. The series resonant circuit that includes L2 and C2q also includes the impedance of the bridge rectifier 4. This includes the circuit that is drawing wireless power, so it can be relatively high. The quality factor of the electromagnetic resonator is given by

$$Q_s = \frac{\omega_i L_2}{R_l} \quad \text{Eq. 1}$$

where ω_i is the angular operating frequency of the inductive WP system and R_l is the equivalent resistance of the diode bridge rectifier 4. Resistance R_l can be relatively high, so the quality factor of this circuit is typically in the low single digits. A value of C_s is chosen such that the resonant frequency of the electromagnetic resonator is equal to the operating frequency of the inductive wireless power system, using the equation

$$\omega_i = \frac{1}{\sqrt{L_2 C_s}} \quad \text{Eq. 2}$$

[0017] FIG. 2 is a schematic diagram illustrating a resonant power receiver circuit 8 used in accordance with the invention that implements a high-Q resonant wireless power receiver. An inductor L2 represents the receiver coil (Rx coil). Capacitors C2a and C2b form a resonant matching network between L2 and the bridge rectifier 10. This matching network is series-parallel because C2a is in series with the load and C2b is in parallel with it. The inductor L2 and

the capacitors C2a and C2b form an electromagnetic resonator. Because some of the inductor current can circulate in a loop including only L2, C2a and C2b (plus parasitic resistance), the quality factor of this electromagnetic resonator can be relatively high, perhaps greater than 100. To choose the values of C2a and C2b, one needs to ensure that their series combination is resonant with L2 at the desired operating frequency ω_r .

$$\omega_r = \frac{1}{\sqrt{L_2 \left(\frac{1}{C_{2a}} + \frac{1}{C_{2b}} \right)}} \quad \text{Eq. 3}$$

[0018] It is preferred in some cases to operate the resonant receiver at a relatively high frequency to maximize the quality factor of the resonator. In other embodiments an operating frequency of 6.78 MHz is used.

[0019] There would be significant utility for a dual-mode wireless power receiver that could receive power from either an inductive charger operating in the 100s of kHz or a resonant charger operating at a frequency in the MHz range. The example discussed here has a low-frequency operating range of 110-205 kHz and a high operation frequency of 6.78 MHz, but the method is generally useful for any two frequency bands separated by a factor of at least 5.

[0020] Although the circuit topologies of the inductive receiver and the resonant receiver are similar, the required inductance and capacitance values are typically quite different, given the different operating frequencies. For a given application, there are some constraints on the usable rectified voltage range. For example, for mobile electronics that use Lithium-ion batteries, it is desirable to produce a regulated 5V supply in order to charge the battery at 3.0 – 4.2 V. Thus the rectified voltage should be chosen in the range of 5V – 15V such that a step-down regulator such as a buck regulator or linear dropout regulator can be selected to produce the regulated 5V supply efficiently. For a dual-mode receiver, this voltage range should be observed in both modes. However, for the same value of receive-coil inductance, a much higher voltage is generated at 6.78 MHz than at 100 kHz, given the fact that induced voltage is expressed

by

$$V_{ind} = \omega M I_1 \quad \text{Eq. 4}$$

where V_{ind} is the induced voltage, M is the mutual inductance, I_1 is the source-coil current and ω is the operating angular frequency. The mutual inductance M is proportional to the square root of the product of the source coil and receiver coil inductances. Thus, it would be advantageous for the dual-mode receiver if the effective inductance of the electromagnetic resonator were higher at low frequencies than at high frequencies.

[0021] FIG. 3 shows the circuit topology 14 of the dual-mode receiver. It has the property that the effective inductance of the electromagnetic resonator is much higher at low frequencies than at high frequencies. This occurs because the capacitor $C2a$ has an impedance much lower than the inductor $L3$ at high frequencies, thus it shunts $L3$. At low frequencies, the two inductors appear in series so as to give the required high inductance value.

[0022] It is possible to make some rough approximations to better understand the operation of the dual-mode receiver. Let us assume that the inductance of $L3$ is 10x the inductance of $L2$. Furthermore, let us assume that the capacitance of $C2q$ is roughly 100x the capacitance of $C2a$ or $C2b$. Finally, let us assume that the capacitors are chosen such that the impedance of $C2q$ is negligibly small at 6.78MHz, and that the impedances of $C2a$ and $C2b$ are negligibly large at 100kHz. One can judge whether the capacitances are negligible by comparing them to the impedance of the inductors.

[0023] At low frequency (100kHz), the $C2a$ and $C2b$ capacitors can be approximated as open circuits. Thus the receiver circuit can be reduced to a pure series LC circuit in which $L2$, $L3$ and $C2q$ are the series elements. The effective inductance is $11 \times L2$. One can choose $C2q$ to combine with this inductance to create a series resonance at 100kHz, as required by the Q_i specification.

[0024] At high frequency (6.78MHz), the $C2q$ capacitor can be modeled as a short circuit. The parallel combination of $C2a$ and $L3$ is dominated by $C2a$. Thus the receiver circuit can be reduced to a series-parallel resonant circuit where $L2$, $C2a$ and $C2b$ are the active elements, similar

to FIG. 2. This circuit can be tuned to resonance at 6.78MHz. The effective inductance of this circuit at high frequency is approximately equal to L_2 , although a small contribution from L_3 can also be observed.

[0025] A wireless power receiver using this coil arrangement and matching network can receive power either from an inductive charger at low frequency (e.g., 100kHz-200kHz) or at high frequency (e.g., 6.78 MHz). The same rectification and regulation produced by the bridge rectifier 4 can be used, thus making maximum use of the active circuitry. The frequency of the ac power can be detected and used to determine which communications protocol to be used, if any.

[0026] The circuit of FIG. 3 can also be used to implement a dual-mode receiver in which high-Q resonances occur at both the first selective frequency and the second selective frequency. Doing so requires a different methodology to choose the component values. For example, suppose that the receiver is intended to support resonant wireless power transfer at 200 kHz and at 6.78 MHz. Suppose that the inductance of L_3 is much larger than that of L_2 , as in the first example. One can choose the capacitance values of C_{2a} and C_{2q} such that L_3 , C_{2a} and C_{2q} form a parallel-series resonator with a resonant frequency of 200 kHz. At 6.78 MHz, L_3 is effectively shunted by C_{2a} . Thus, one can choose the value of C_{2b} such that L_3 , C_{2a} , C_{2q} and C_{2b} form a series-parallel resonator with a resonant frequency of 6.78 MHz. Both resonators have high intrinsic quality factor because, unlike in the inductive receiver circuit, there exists a path for circulating current that comprises only passive elements.

[0027] In some inductive wireless power standards, load modulation may be used for in-band communications. The load modulation may be implemented through the use of switched capacitors C_c , as shown in FIG. 4. These capacitors C_c apply some detuning when switched in, presenting a variation in the impedance seen by the source amplifier, which can be decoded to recover some information. The value of the capacitors C_c is typically on the order of the C_{2q} capacitor. In the high-frequency resonant mode, these capacitors can be used as voltage clamps. Switching in the C_c capacitors couples the input terminals

of the rectifier to ground with a low ac impedance. This can be used as a protection mechanism, to limit the ac voltage applied to the terminals of an IC that has a maximum voltage tolerance.

[0028] FIG. 5 shows a coil arrangement 18 that can form two separate inductors in the same plane of a printed circuit board, making it possible to save circuit area. In the example of FIG. 5, the two inductors are arranged in a planar, concentric fashion with the L3 inductor on the inside and the L2 inductor on the outside. The orientation can also be reversed such that the L3 inductor is on the outside and the L2 inductor is on the inside. Realizing the inductive coil elements in a planar arrangement is advantageous because the thickness of the coil assembly can be minimized. Realizing the inductive coil elements in a concentric fashion is advantageous because it makes maximal use of a limited space. Both area and thickness may be highly constrained in a portable electronic device. The two coils have mutual inductance to each other, but this effect can be accounted for in the tuning network. Other embodiments can use different arrangements to satisfy the requirements of inductors L2 and L3. The connection points 1-3 illustrate the interconnection points for the overall concentric arrangement 18. In addition to a printed circuit board, any planar mass-production process may be used to implement the inductive coil arrangement.

[0029] The diode bridge rectifier 4 can be replaced with a synchronous rectifier 22 in any of the receiver circuits to reduce ohmic losses as shown in FIG. 6. The synchronous rectifier 22 improves the efficiency of rectification by replacing diodes with actively controlled switches such as transistors, usually power MOSFETs or power BJTs. Historically, vibrator driven switches or motor-driven commutators have also been used for mechanical rectifiers and synchronous rectification, which also be used in accordance with the invention.

[0030] Essentially, the invention describes a receiver-side circuit that can operate either in a low-frequency inductive charging system such as Qi or a higher-frequency resonant wireless power system. The invention allows for the use of complicated coil arrangements and

one more passive component than a single-mode receiver. Moreover, the dual-mode wireless power receiver can have a low-frequency operating range of 110-205 kHz and a high operation frequency of 6.78 MHz, but the invention can generally be used for any two frequency bands separated by a factor of at least 5.

[0031] Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

Claims

What is claimed is:

1. A dual-mode receiver comprising an electromagnetic resonator that includes one or more inductive elements that are arranged to form a receiver coil and a network of passive components arranged to form a matching network, the electromagnetic resonator having a first selective frequency defined in a low frequency range and a second selective frequency defined in a high frequency range allowing for a rectification circuit to operate in both the high frequency range and low frequency range making maximum use of active circuits.
2. The dual-mode receiver of claim 1, wherein the one or more inductive elements are arranged to produce a low-Q inductive charging receiver in the low frequency range.
3. The dual-mode receiver of claim 1, wherein the one or more inductive elements are arranged to produce a high-Q inductive charging receiver in the high frequency range.
4. The dual-mode receiver of claim 1, wherein the rectification circuits comprise a bridge rectifier.
5. The dual-mode receiver of claim 1, wherein the rectification circuits comprise a synchronous rectifier.
6. The dual-mode receiver of claim 1, wherein the electromagnetic resonator comprises an inductive wireless component and a resonant wireless power component.
7. The dual-mode receiver of claim 1, wherein the effective inductance of the electromagnetic resonator is lowered at the high frequency range.
8. The dual-mode receiver of claim 1, wherein the effective inductance of the electromagnetic resonator is increased at the low frequency range.
9. The dual-mode receiver of claim 1, wherein the one or more inductive elements comprise two inductive elements designed to receive low-frequency power and high-frequency power, and are fabricated in the same plane of a printed circuit board.
10. The dual-mode receiver of claim 1, wherein the one or more inductive elements are arranged in a concentric manner with the

high-frequency element on the outside.

11. The dual-mode receiver of claim 1, where the one or more inductive elements are arranged in a concentric manner with the high-frequency element on the inside.

12. The dual-mode receiver of claim 1, wherein high-Q resonances occur at both the first selective frequency and the second selective frequency.

13. A wireless receiver comprising an electromagnetic resonator that includes one or more inductive elements that are arranged to form a receiver coil and a network of passive components arranged to form a matching network, the electromagnetic resonator having a first selective frequency defined in a low frequency range and a second selective frequency defined in a high frequency range allowing for a rectification circuit to operate in both the high frequency range and low frequency range making maximum use of active circuits.

14. The wireless receiver of claim 13, wherein the one or more inductive elements are arranged to produce a low-Q inductive charging receiver in the low frequency range.

15. The wireless receiver of claim 13, wherein the one or more inductive elements are arranged to produce a high-Q inductive charging receiver in the high frequency range.

16. The wireless receiver of claim 13, wherein the rectification circuits comprise a bridge rectifier.

17. The wireless receiver of claim 13, wherein the rectification circuits comprise a synchronous rectifier.

18. The wireless receiver of claim 13, wherein the electromagnetic resonator comprises an inductive wireless component and a resonant wireless power component.

19. The wireless receiver of claim 13, wherein the effective inductance of the electromagnetic resonator is lowered at the high frequency range.

20. The wireless receiver of claim 13, wherein the effective inductance of the electromagnetic resonator is increased at the low frequency range.

21. The wireless receiver of claim 13, wherein the one or more

inductive elements comprise two inductive elements designed to receive low-frequency power and high-frequency power, and are fabricated in the same plane of a printed circuit board.

22. The wireless receiver of claim 13, wherein the one or more inductive elements are arranged in a concentric manner with the high-frequency element on the outside.

23. The wireless receiver of claim 13, where the one or more inductive elements are arranged in a concentric manner with the high-frequency element on the inside.

24. The wireless receiver of claim 13, wherein high-Q resonances occur at both the first selective frequency and the second selective frequency.

25. A method of performing the operations of a wireless receiver comprising:

arranging an electromagnetic resonator to include one or more inductive elements that are arranged to form a receiver coil and a network of passive components arranged to form a matching network; and

providing the electromagnetic resonator having a first selective frequency defined in a low frequency range and a second selective frequency defined in a high frequency range allowing for a rectification circuit to operate in both the high frequency range and low frequency range making maximum use of active circuits.

26. The method of claim 25, wherein the one or more inductive elements are arranged to produce a high-Q inductive charging receiver in the low frequency range.

27. The method of claim 25, wherein the one or more inductive elements are arranged to produce a low-Q inductive charging receiver in the high frequency range.

28. The method of claim 25, wherein the rectification and regulation circuits comprise a bridge rectifier.

29. The method of claim 25, wherein the rectification and regulation circuits comprise a synchronous rectifier.

30. The method of claim 25, wherein the electromagnetic resonator comprises an inductive wireless component and a resonant wireless

power component.

31. The method of claim 25, wherein the effective inductance of the electromagnetic resonator is lowered at the high frequency range.

32. The method of claim 25, wherein the effective inductance of the electromagnetic resonator is increased at the low frequency range.

33. The method of claim 25, wherein the one or more inductive elements comprise two inductive elements designed to receive low-frequency power and high-frequency power, and are fabricated in the same plane of a printed circuit board.

34. The method of claim 25, wherein the one or more inductive elements are arranged in a concentric manner with the high-frequency element on the outside.

35. The method of claim 25, where the one or more inductive elements are arranged in a concentric manner with the high-frequency element on the inside.

36. The method of claim 25, wherein high-Q resonances occur at both the first selective frequency and the second selective frequency.

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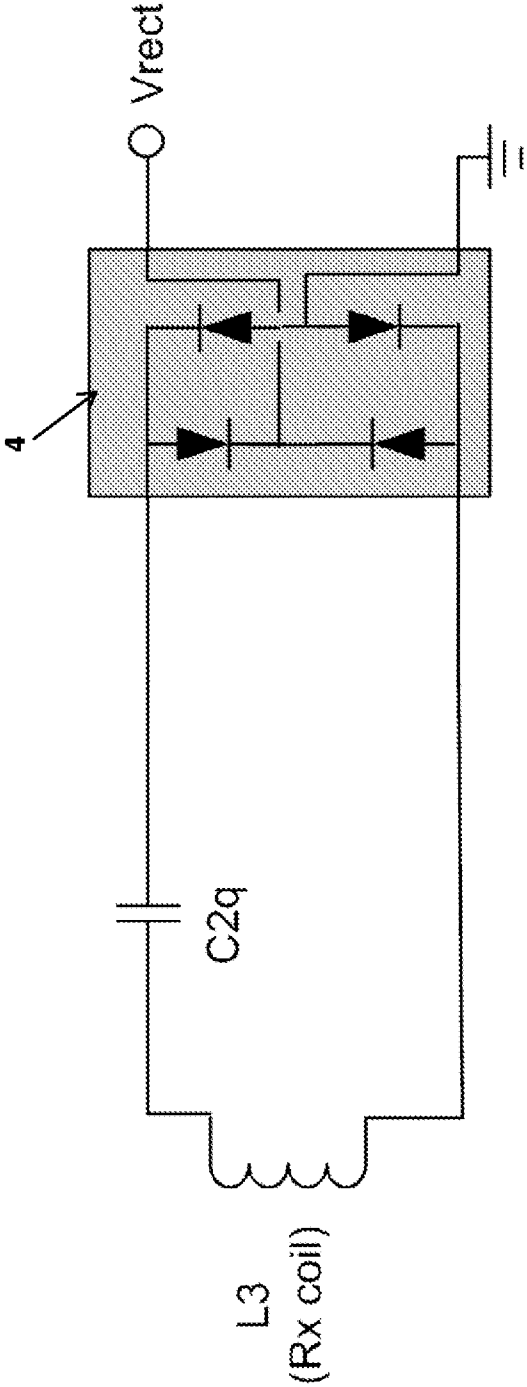


FIG. 1

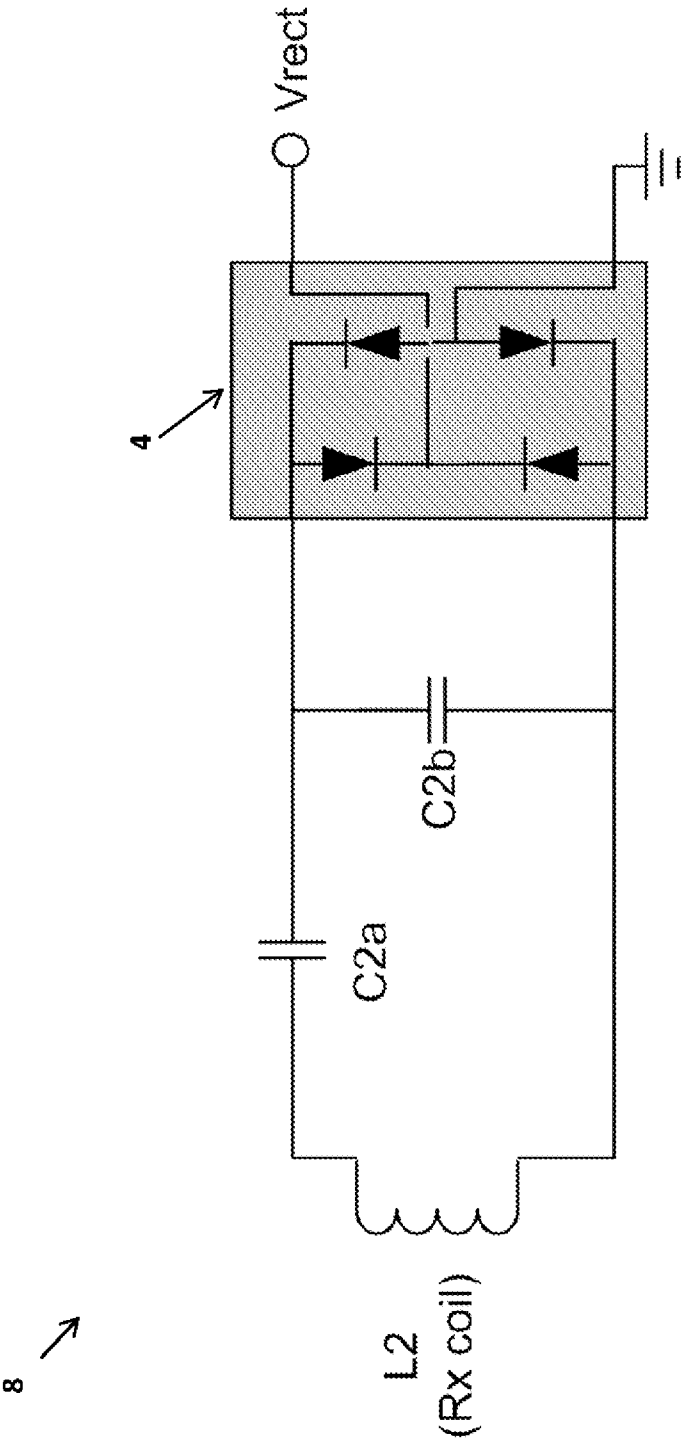


FIG. 2

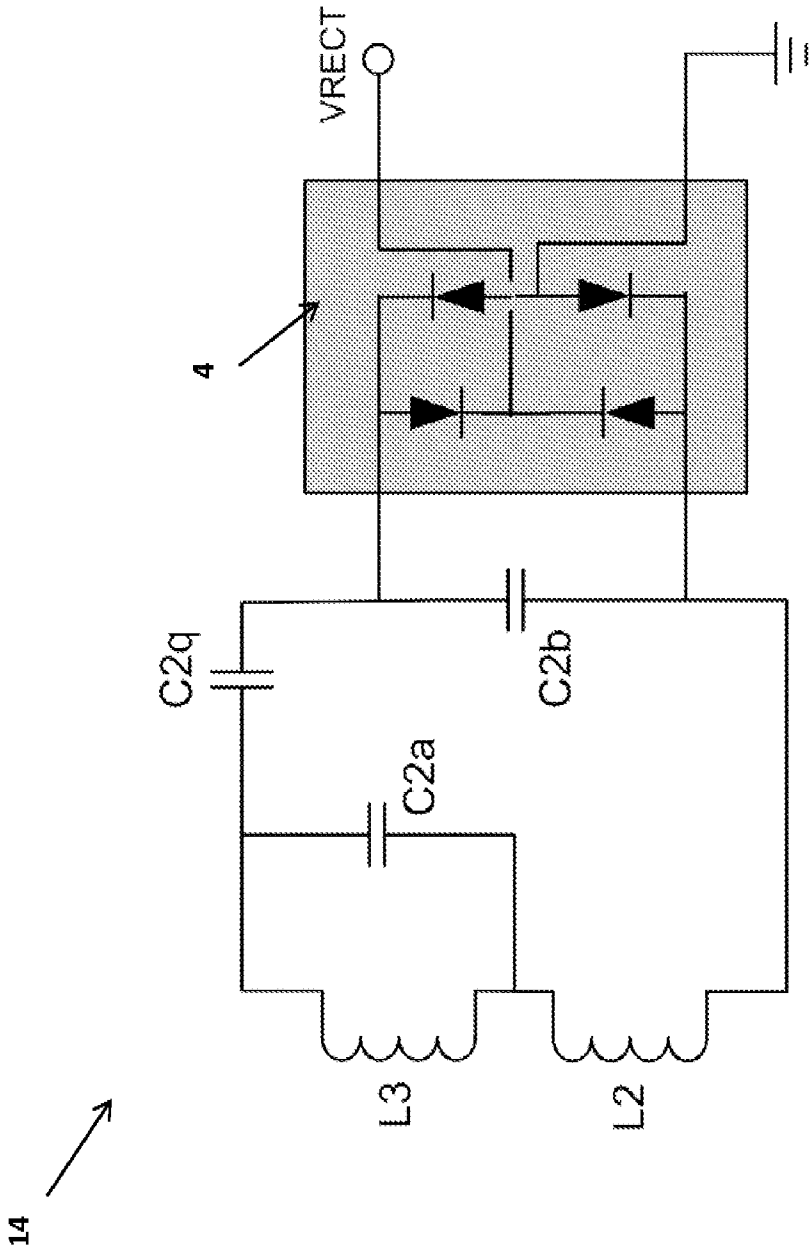


FIG. 3

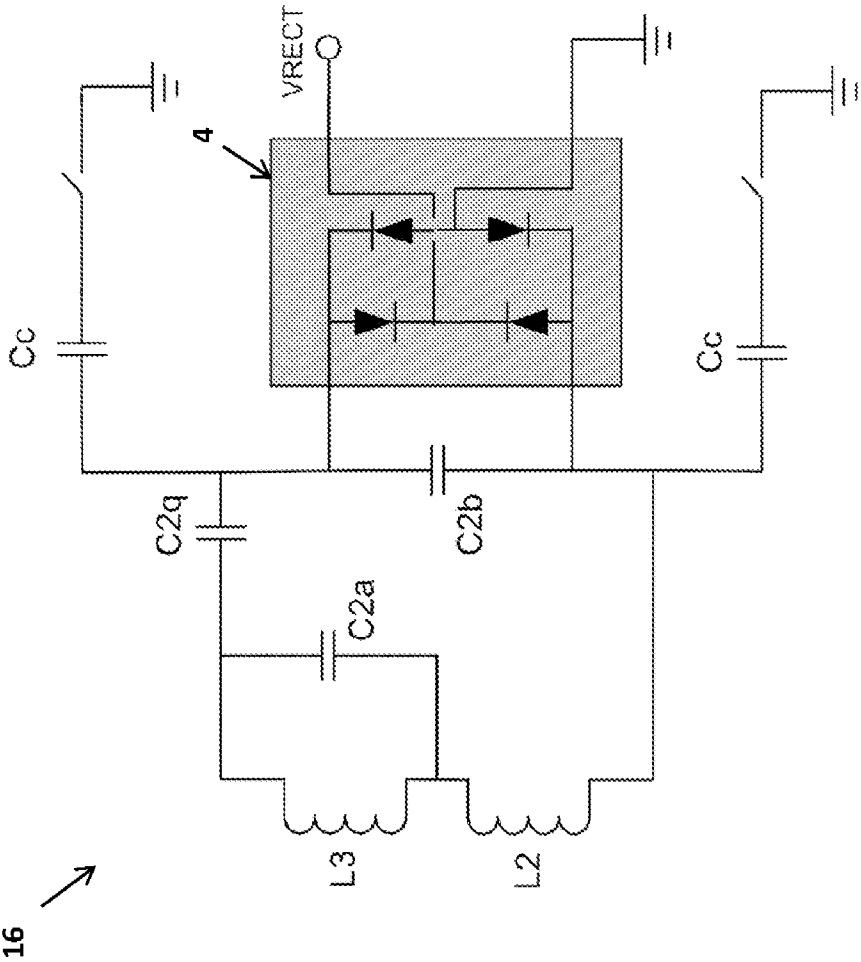


FIG. 4

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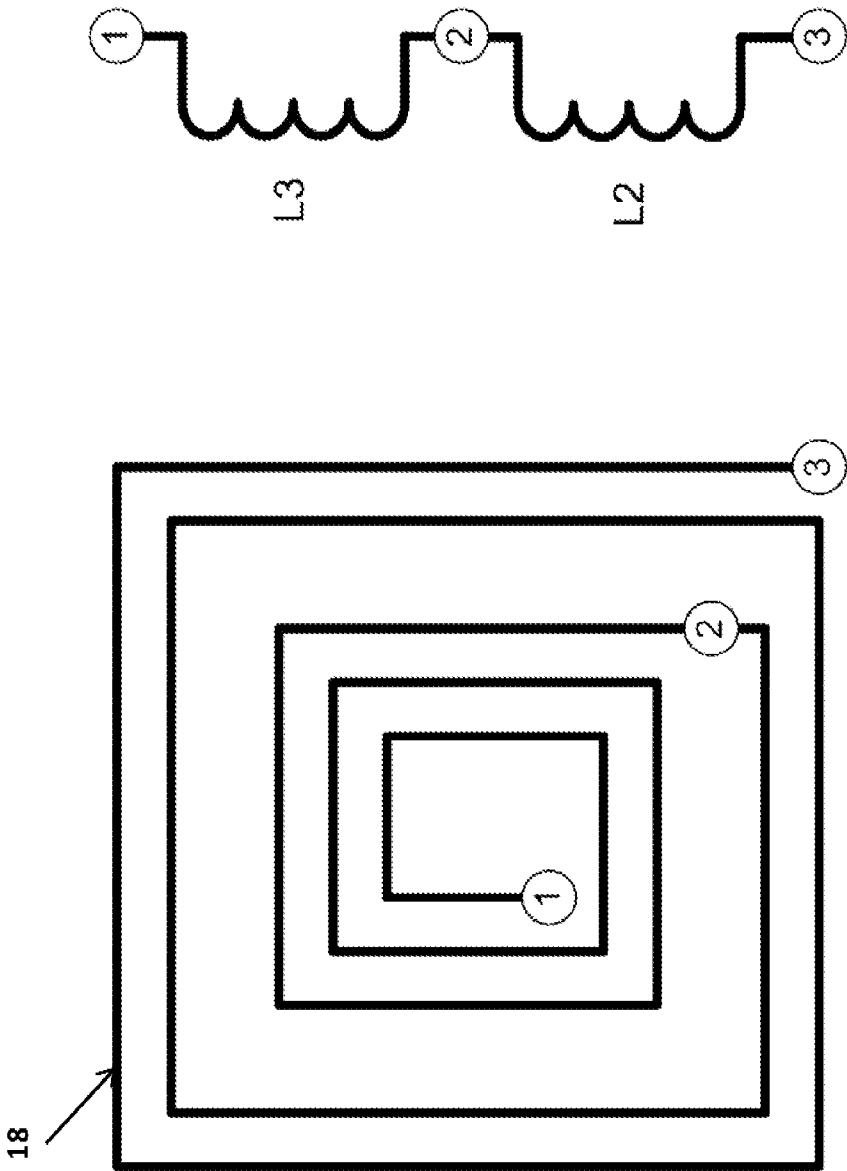


FIG. 5

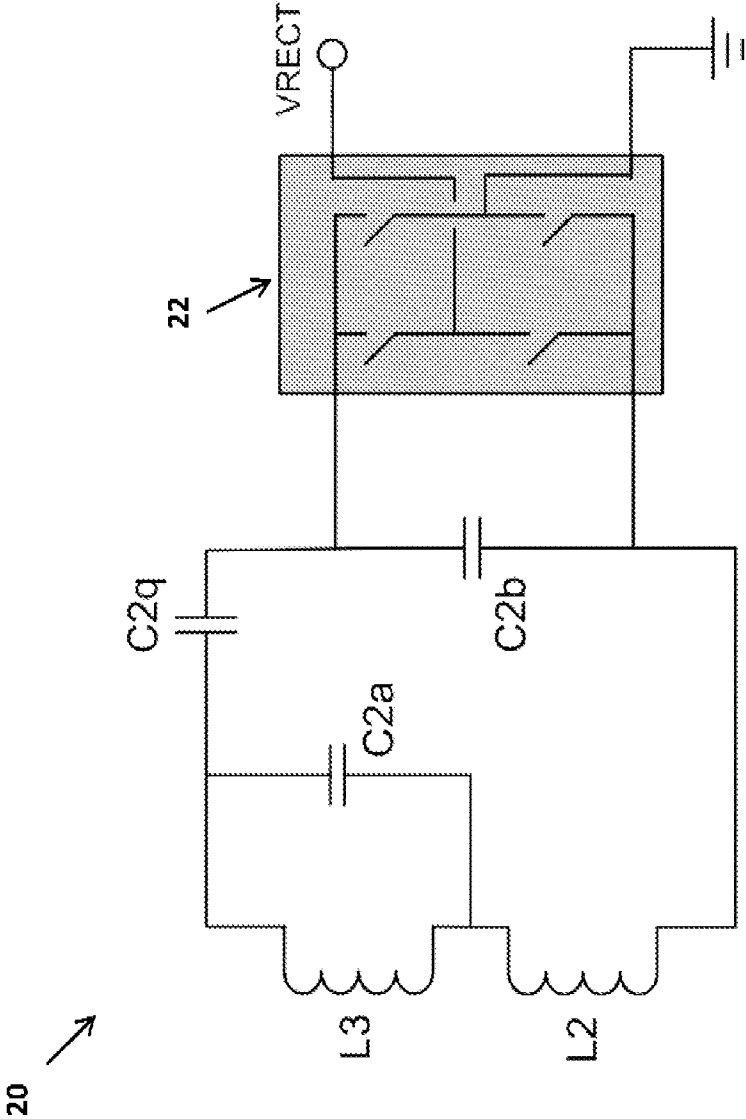


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 14/17505

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H01F 38/00 (2014.01)

USPC - 307/104

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)

USPC: 307/104

IPC(8) - H01F 38/00 (2014.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 320/107,108; 307/104 (keyword limited; terms below)

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

Patbase; Google Scholar; Google Patents

Search terms used: Dual; power; receiver; inductor; resonator; low frequency; high frequency; rectifier; bridge; synchronous; Q-factor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2013/0049484 A1 (WEISSENTERN et al.) 28 February 2013 (28.02.2013), entire document especially Abstract, para [0025], para [0115], para [0118]-[0119], para [0138], para [0220]-[0222])	1-36
Y	US 2011/0169338 A1 (KOZAKAI) 14 July 2011 (14.07.2011) entire document especially para [0061], para [0090], para [0142]-[0143].	1-36
Y	US 2012/0262004 A1 (COOK et al.) 18 October 2012 (18.10.2012) entire document especially Abstract, para [0084], para [0086].	1-36
A	US 2010/0190435 A1 (COOK et al.) 29 July 2010 (29.07.2010), entire document, especially; para [0031], [0035], [0036], [0038], [0045]	1-36
A	US 2007/0222542 A1 (JOANNOPOULOS et al.) 27 September 2007 (27.09.2007), entire document	1-36
A	US 2010/0068998 A1 (ZYAMBO et al.) 18 March 2010 (18.03.2010), entire document	1-36
A	US 2013/0043727 A1 (LIU et al.) 21 February 2013 (21.02.2013), entire document	1-36

☐ Further documents are listed in the continuation of Box C.

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Date of the actual completion of the international search

17 May 2014 (17.05.2014)

Date of mailing of the international search report

13 JUN 2014

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