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(54) **COMMUNICATION IN WIRELESS ENERGY TRANSFER SYSTEMS**

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(60) Provisional application No. 61/896,290, filed on Oct. 28, 2013, provisional application No. 61/974,911, filed on Apr. 3, 2014, provisional application No. 61/378,600, filed on Aug. 31, 2010, provisional application No. 61/411,490, filed on Nov. 9, 2010, provisional application No. 61/523,998, filed on Aug. 16, 2011.

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H02J 7/02	(2006.01)
H01F 38/14	(2006.01)

(52) **U.S. Cl.**

CPC ***H04B 5/0037*** (2013.01); ***H01F 38/14*** (2013.01); ***H02J 5/005*** (2013.01); ***H02J 7/025*** (2013.01)

USPC **307/104**

(57) **ABSTRACT**

Improved configurations for wireless energy transfer can include system elements of a wireless energy transfer system that may pair in-band and out-of-band communication channels by exchanging related information. Energy transfer signals may be modulated according to defined waveforms. Information about the signal may be transmitted using an out-of-band communication channel. A system element that receives both the signal and information may verify that they correspond to the same system element.

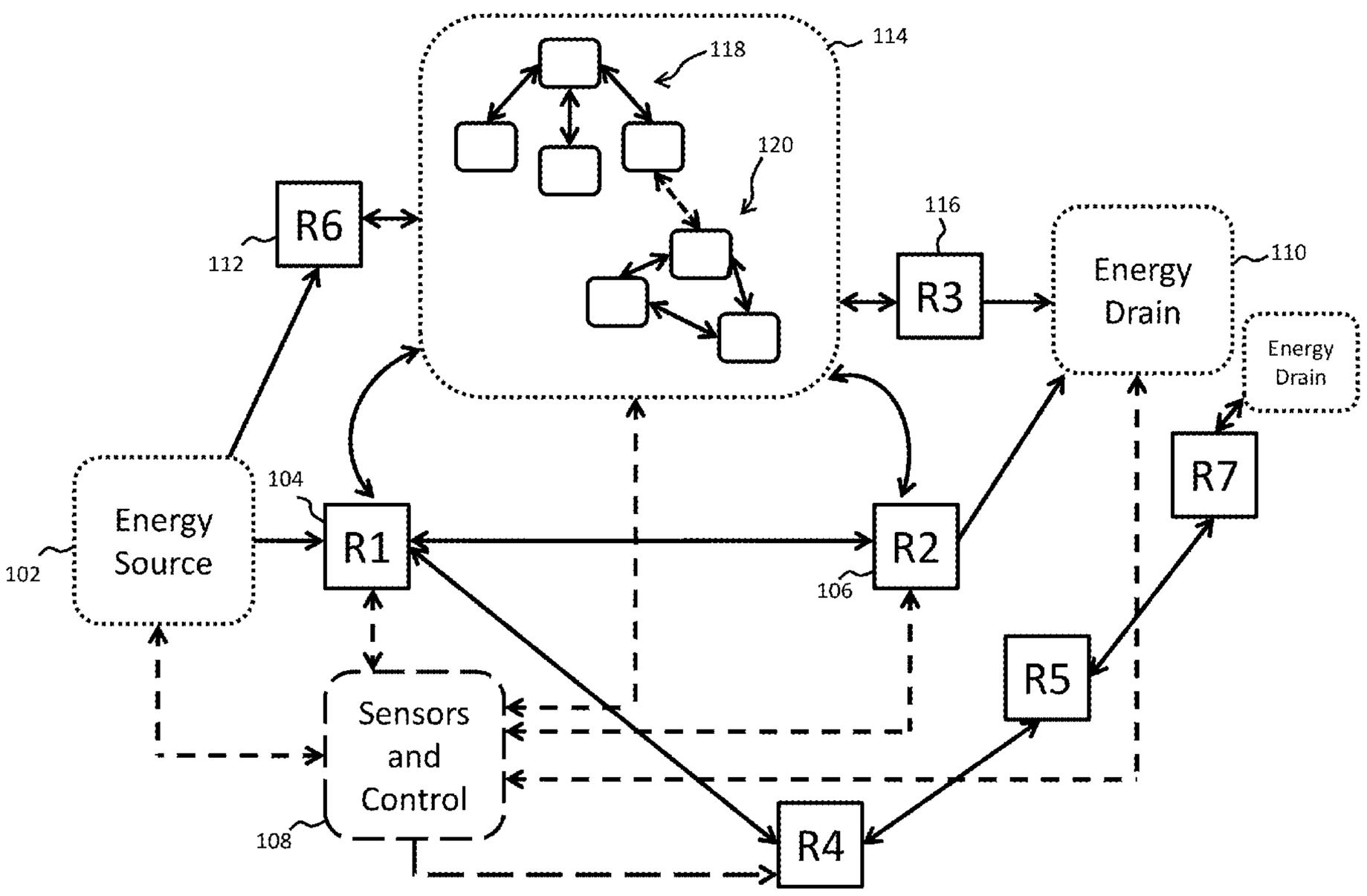
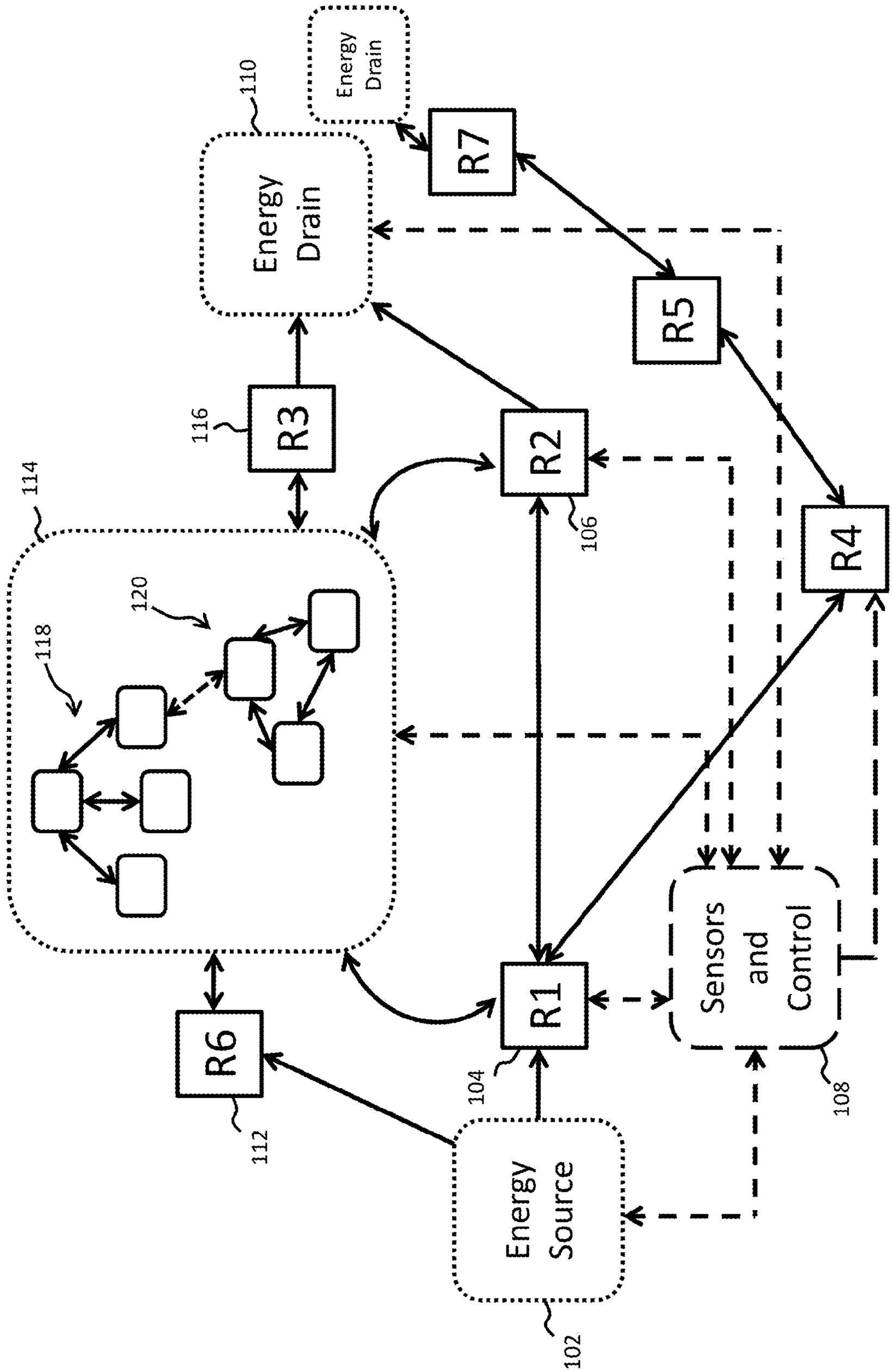


Fig. 1


Energy Source
102
R1
104
R2
106
R3
116
R4
R5
R6
112
R7
Energy Drain
110
Energy Drain
114
118
120
Sensors and Control
108

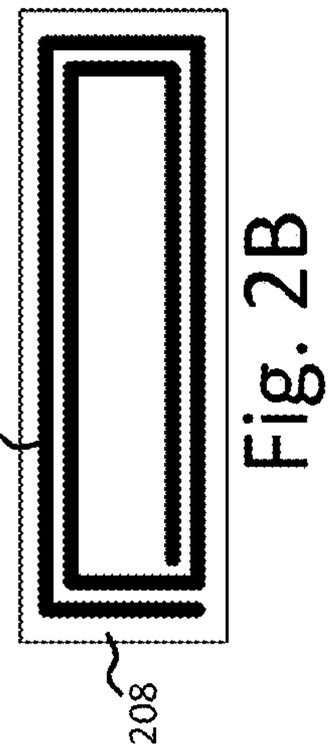


Fig. 2B

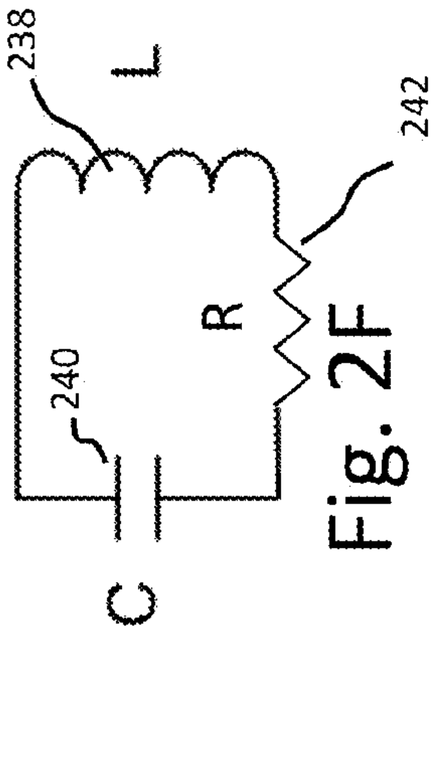


Fig. 2F

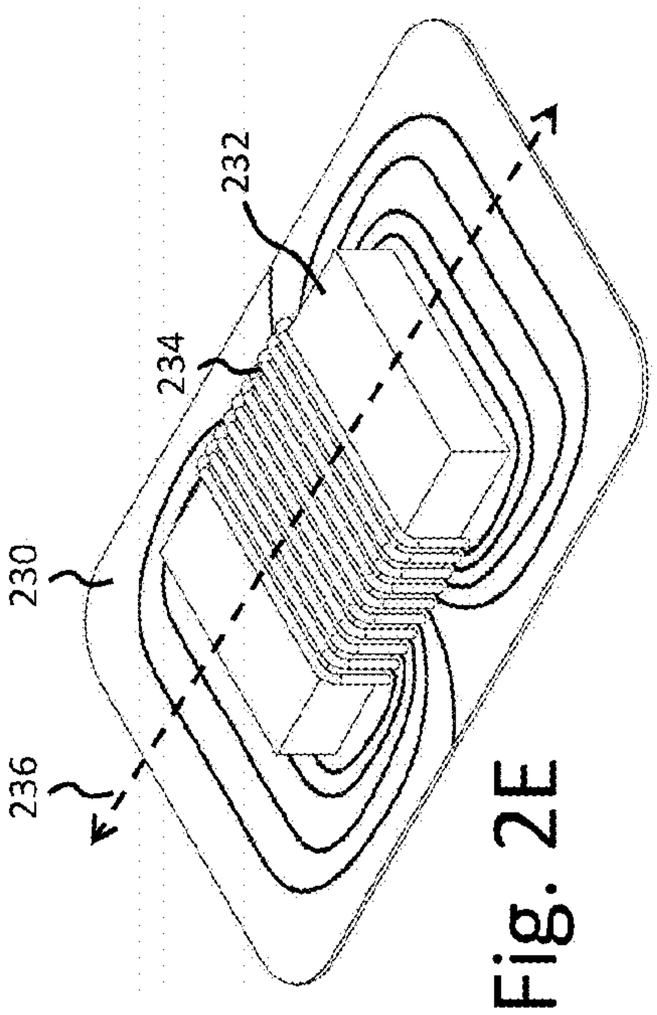


Fig. 2E

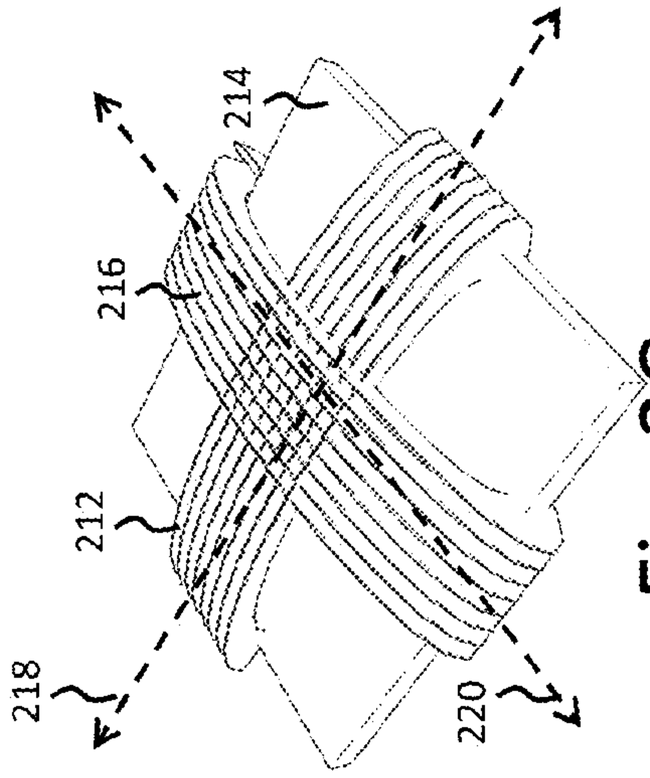


Fig. 2C

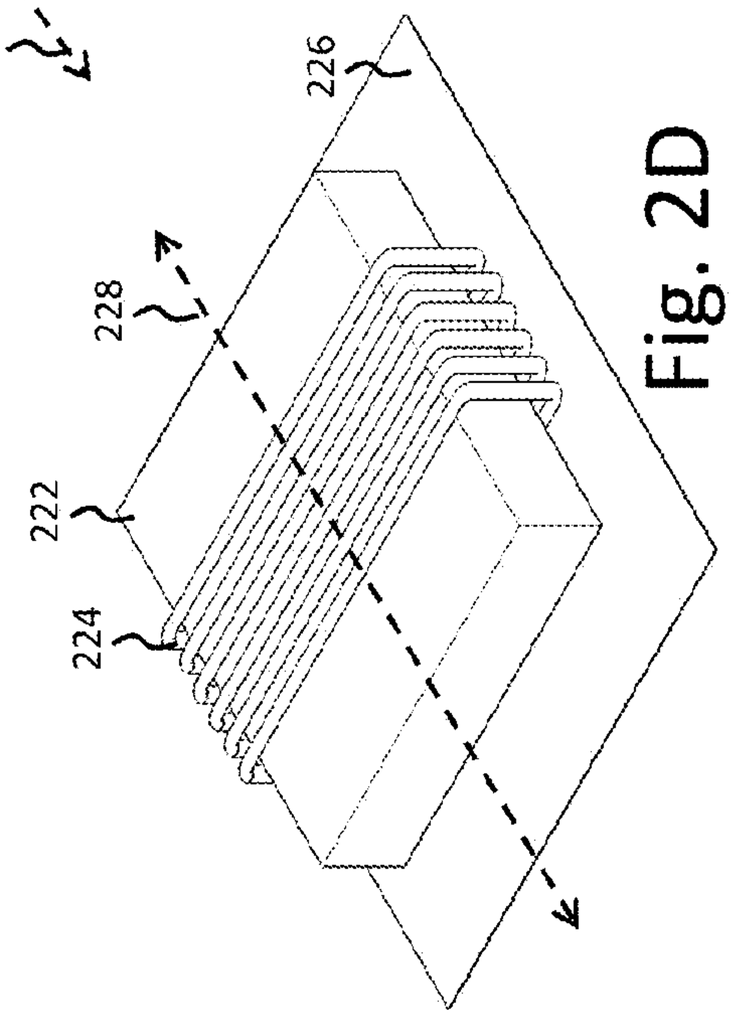


Fig. 2D

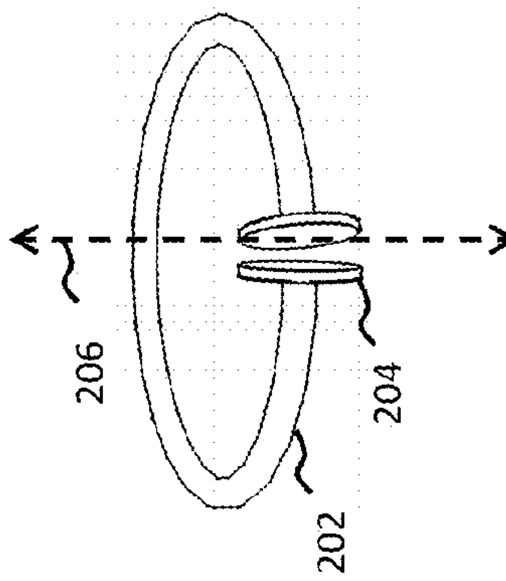


Fig. 2A

Fig. 3

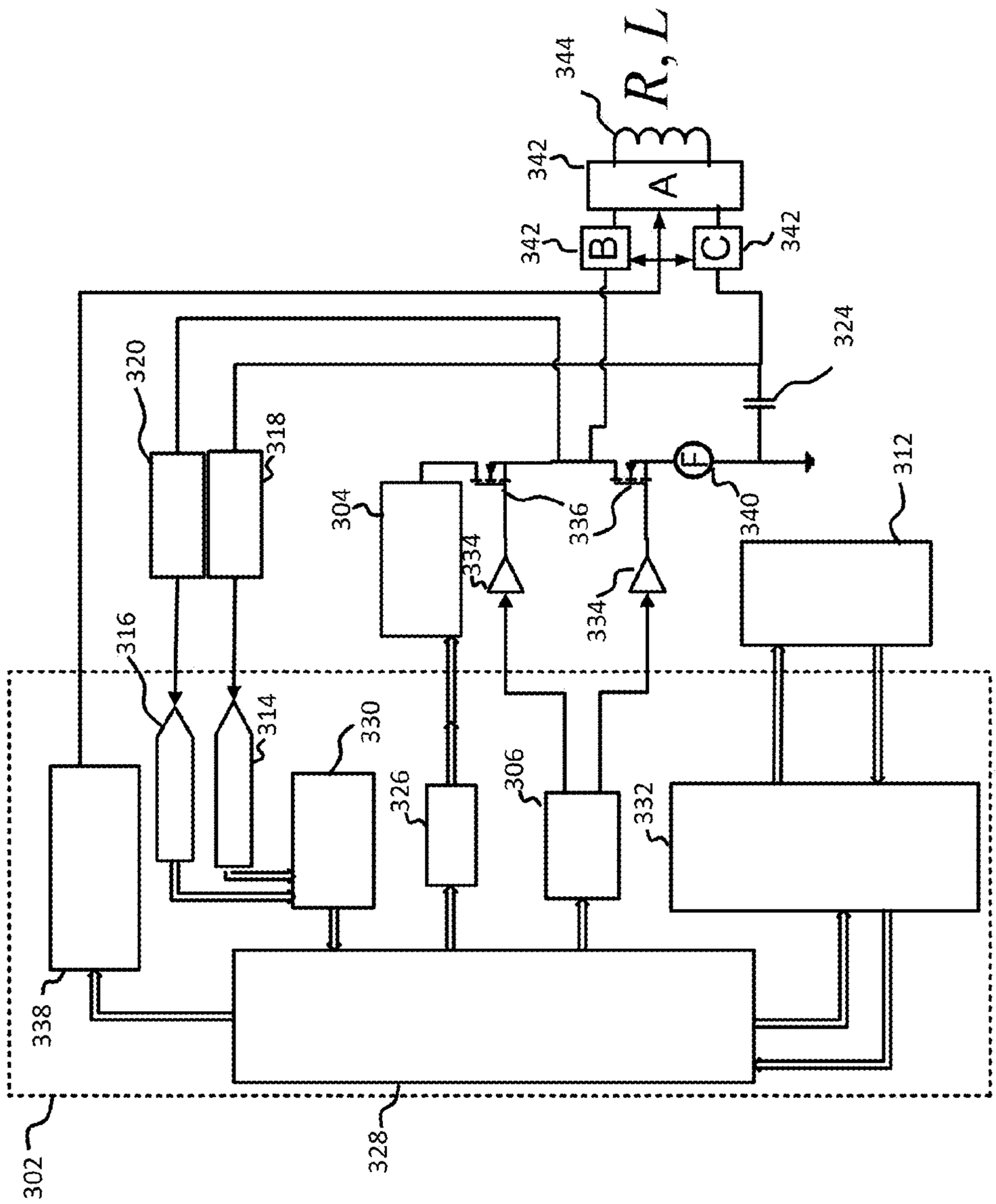
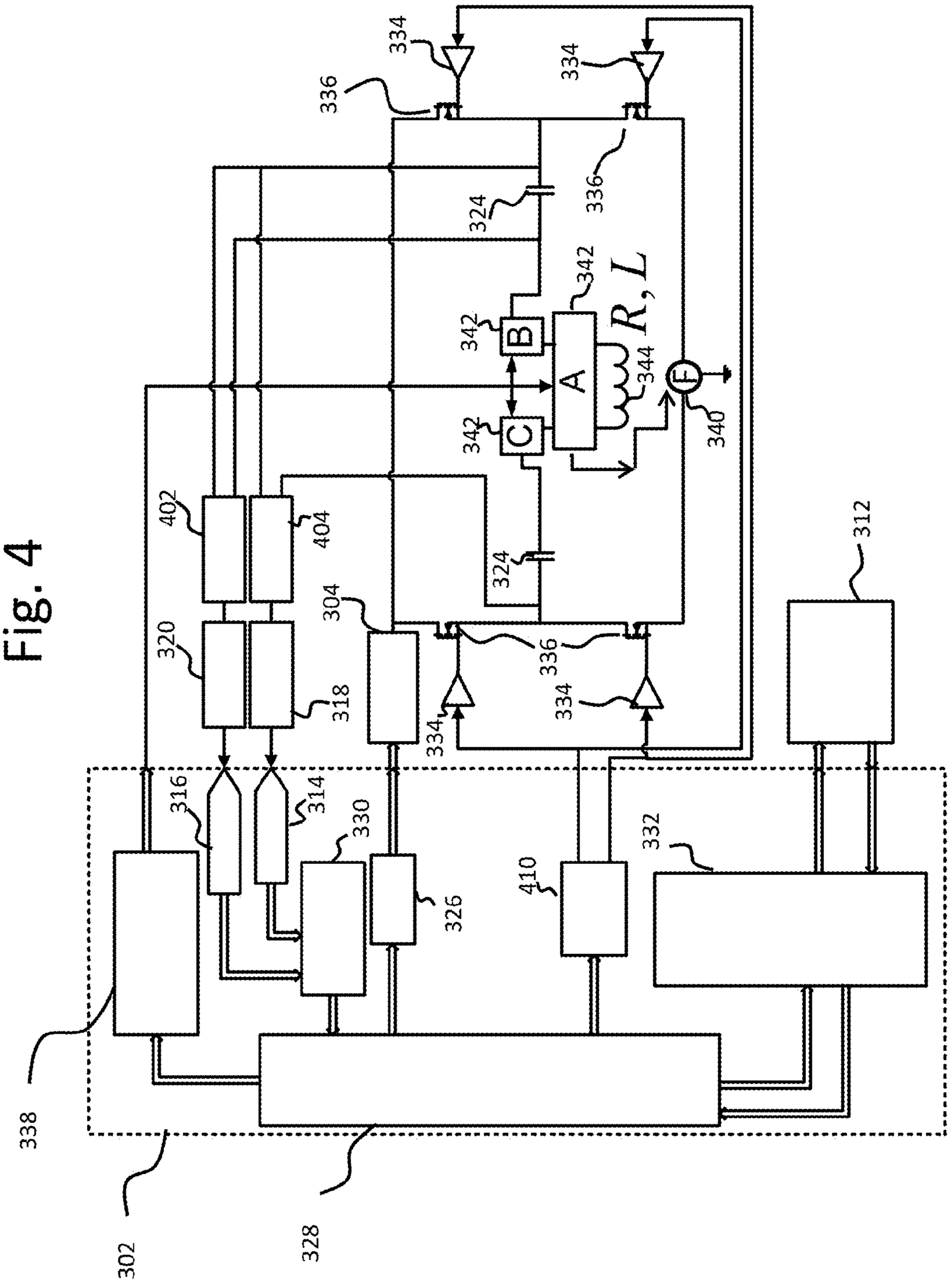

344
L
R
342
A
342
B
C
342
324
320
318
304
336
334
334
340
312
316
314
330
326
306
332
338
302
328

Fig. 4


334
336
334
336
324
342
B
A
C
R, L
344
342
342
340
F
402
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326
410
332
338
302
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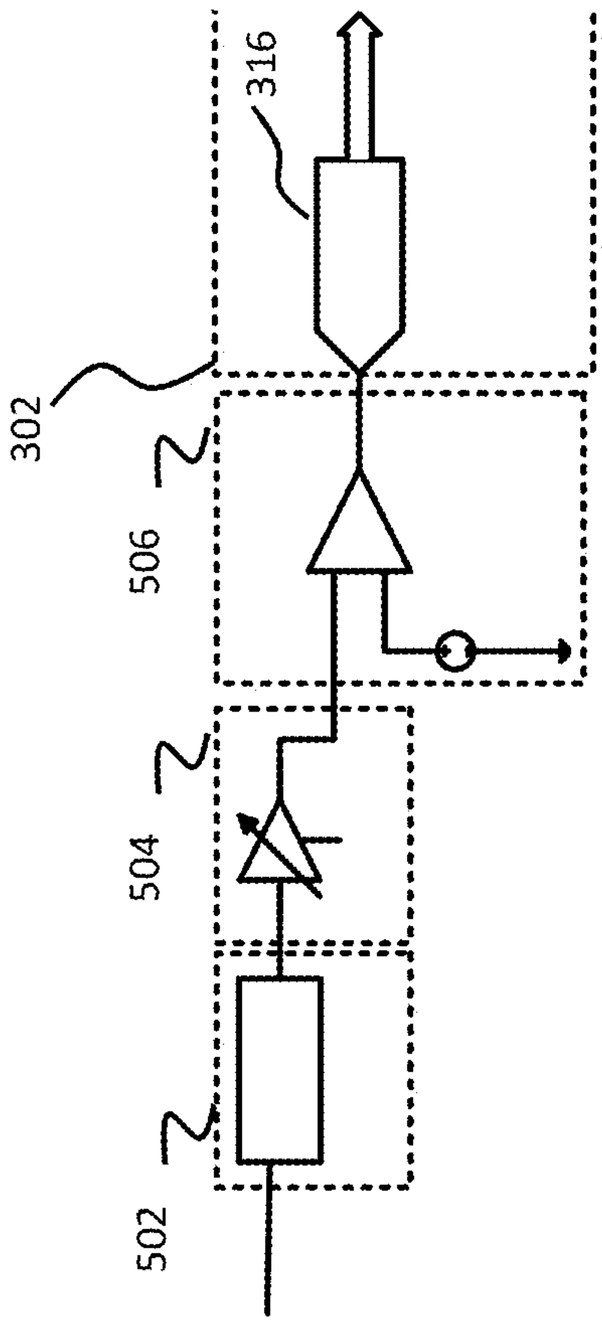


Fig. 5A

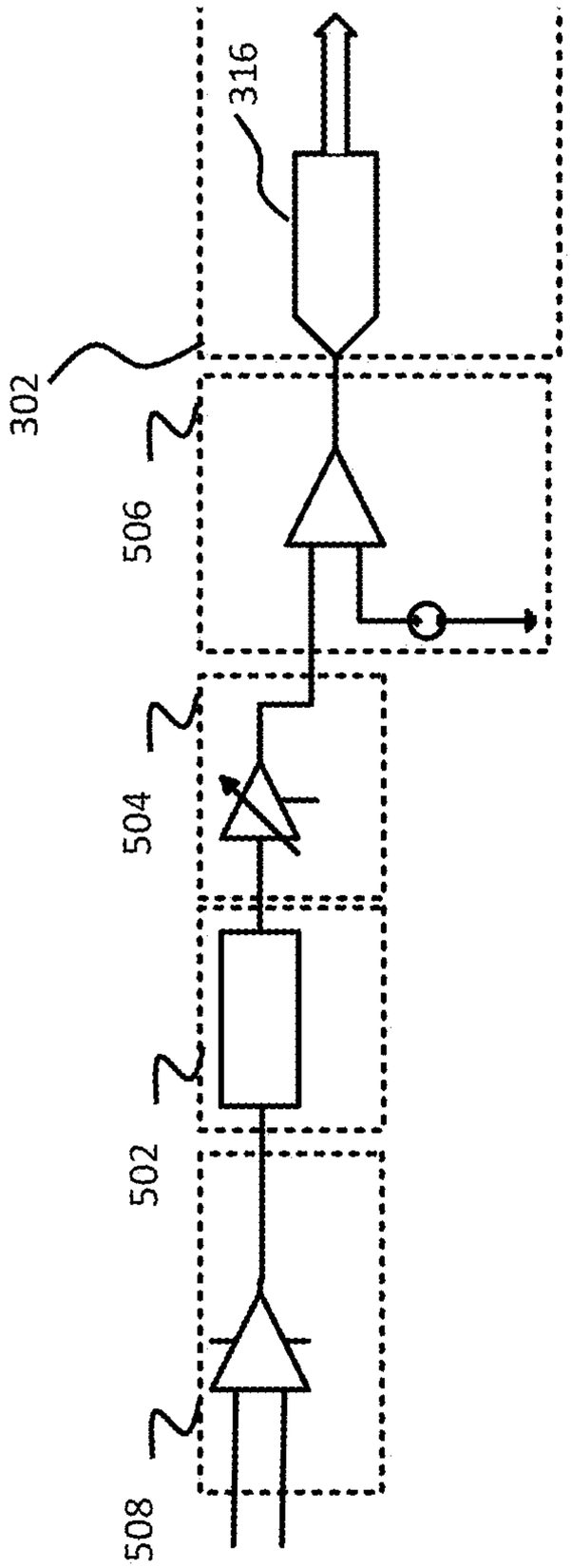


Fig. 5B

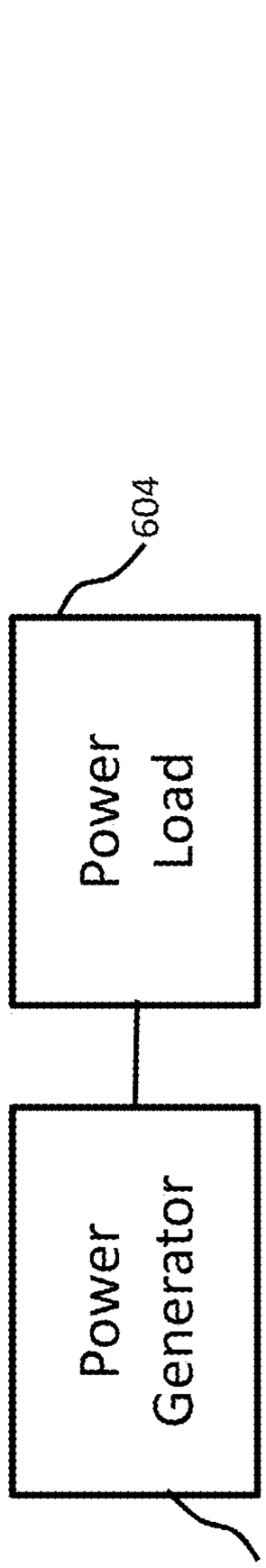


Fig. 6A

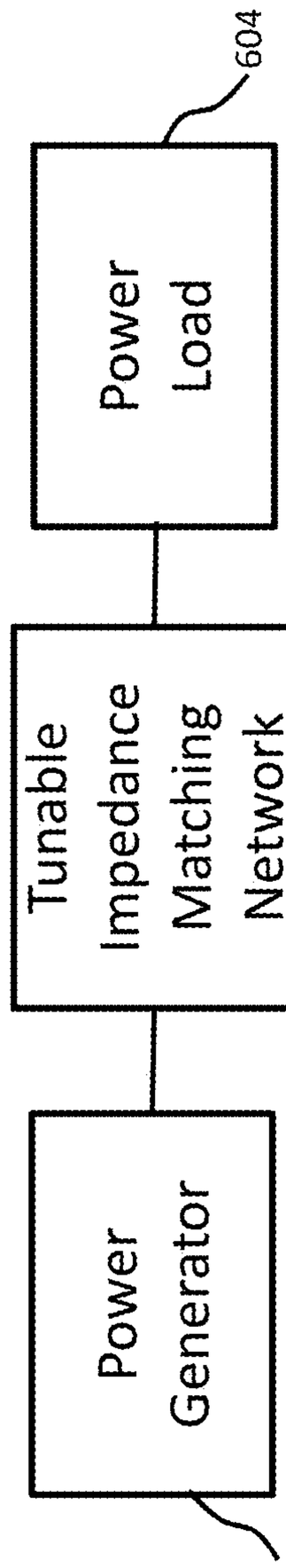


Fig. 6B

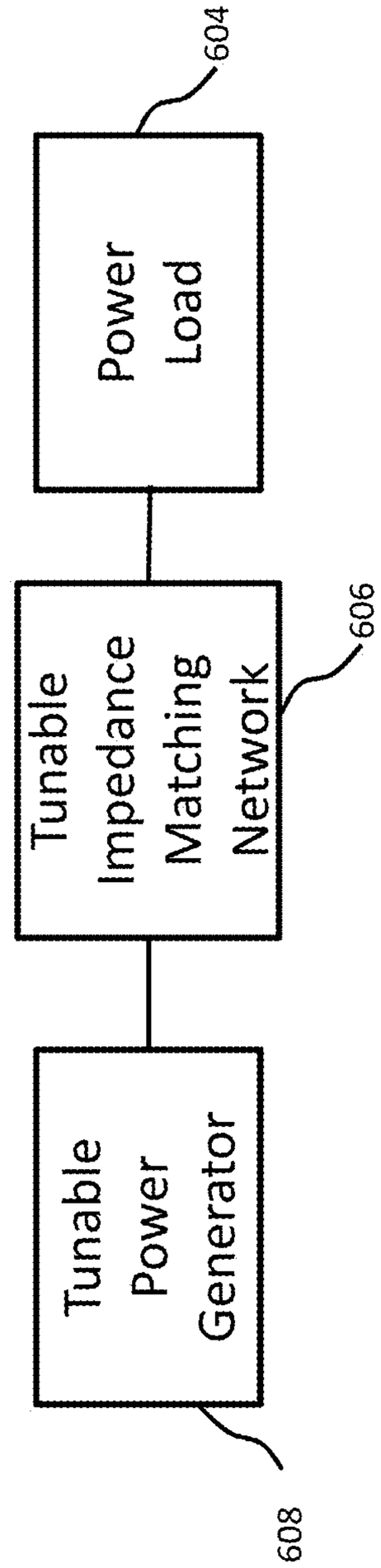


Fig. 6C

Fig. 7

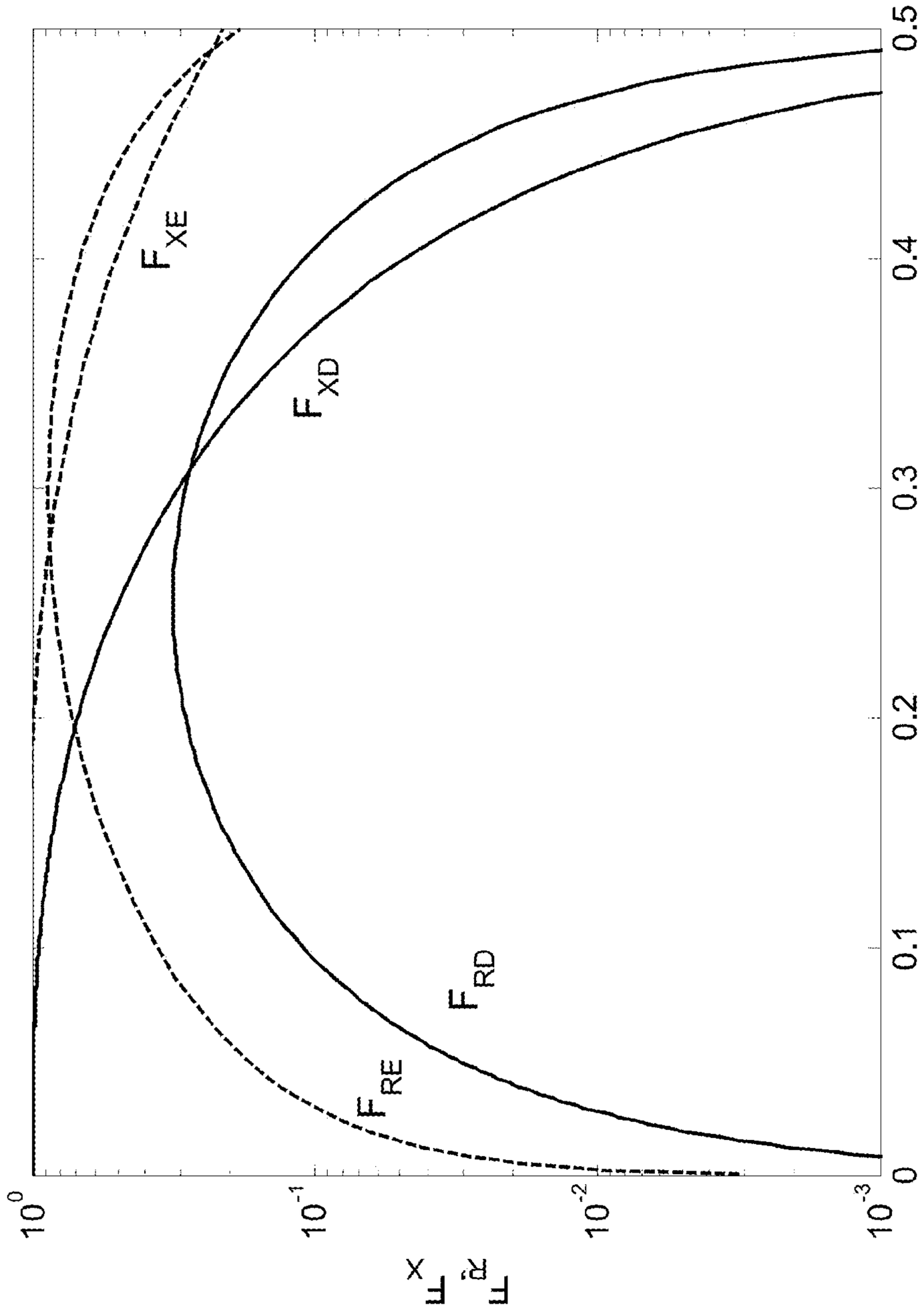

F_{XE}
F_{XD}
F_{RD}
F_{RE}
F_X, F_R
10^0
10^{-1}
10^{-2}
10^{-3}
0.5
0.4
0.3
0.2
0.1
0
duty cycle dc

Fig. 8

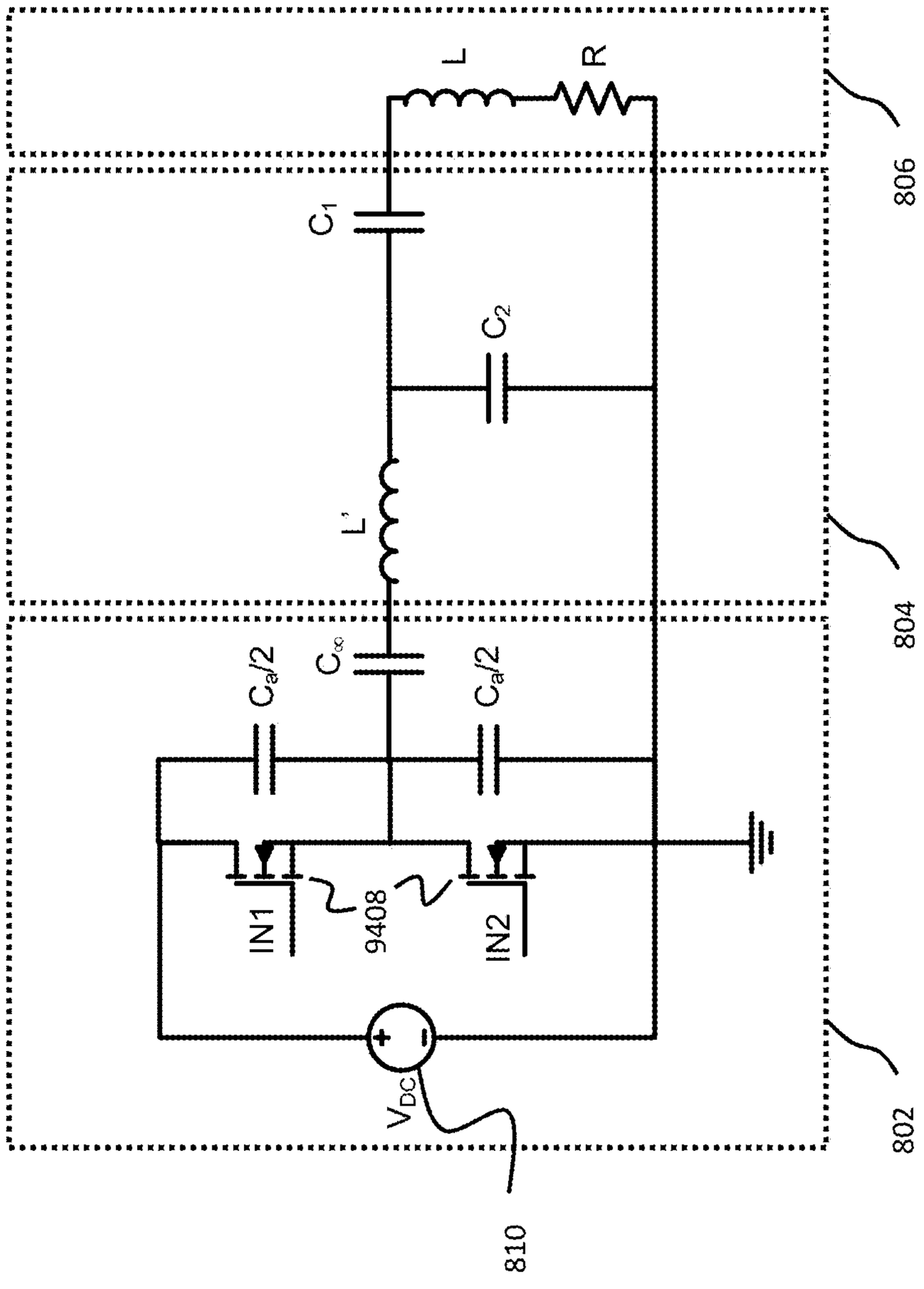


Fig. 9

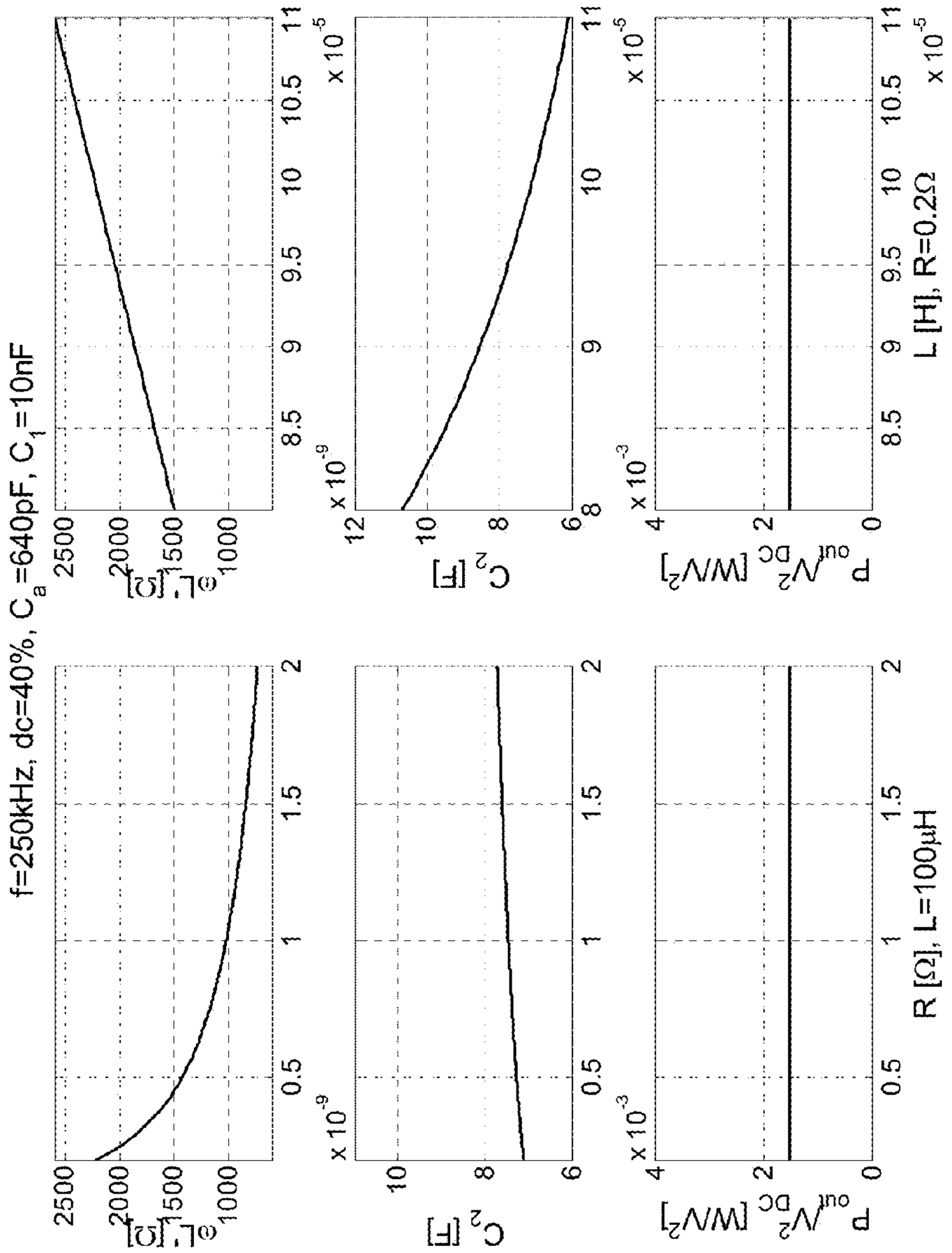

f=250kHz, dc=40%, C_a=640pF, C_1=10nF
ωL_1 [Ω]
C_2 [F]
P_{out}/V^2_{DC} [W/V²]
L [H], R=0.2Ω
R [Ω], L=100μH
x 10⁻⁵
x 10⁻⁹
x 10⁻³

Fig. 10

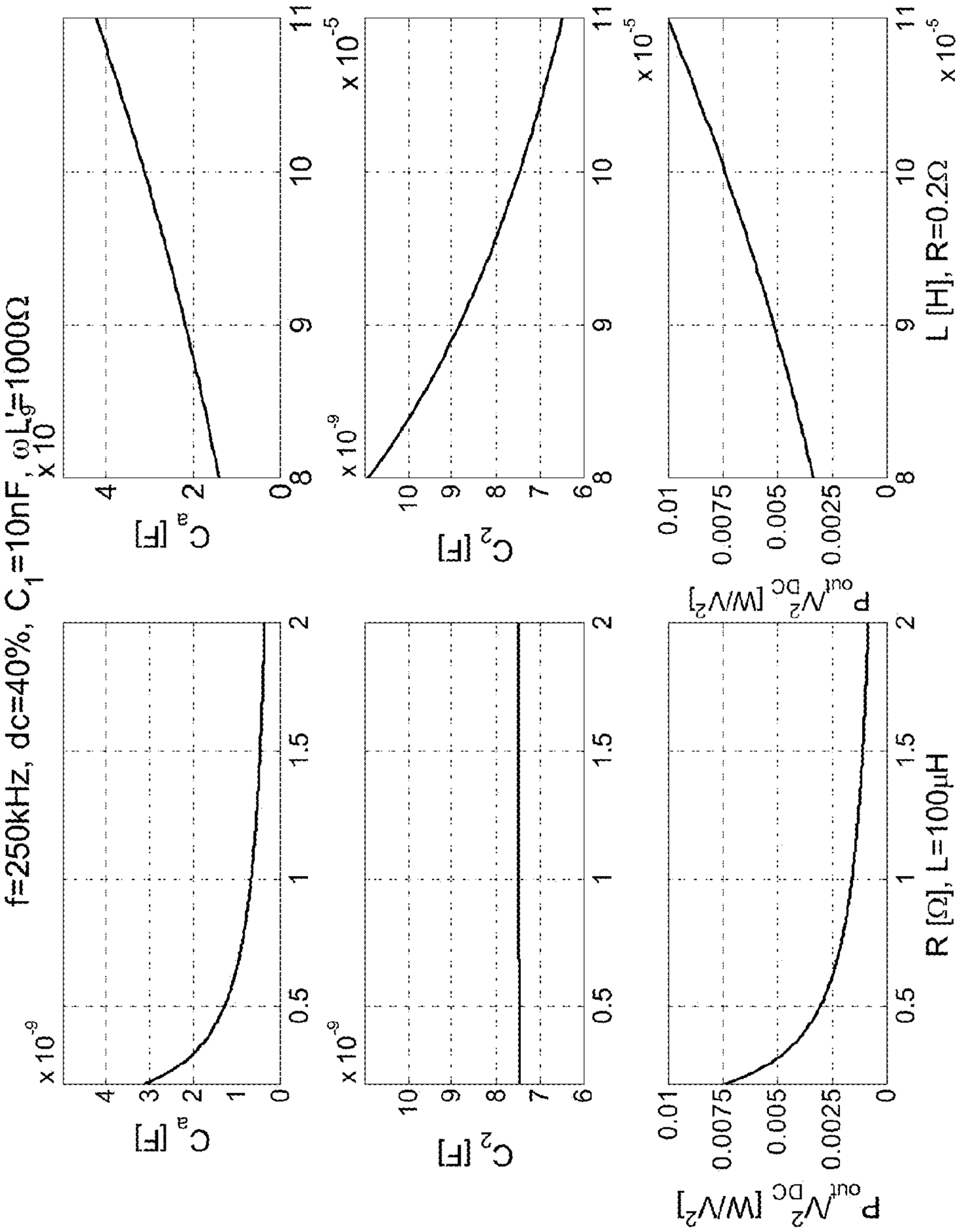

f=250kHz, dc=40%, C1=10nF, ωL'g=1000Ω
R [Ω], L=100μH
L [H], R=0.2Ω
Ca [F]
C2 [F]
Pout/VDC2 [W/V2]
x 10-9
x 10-5

Fig. 11A

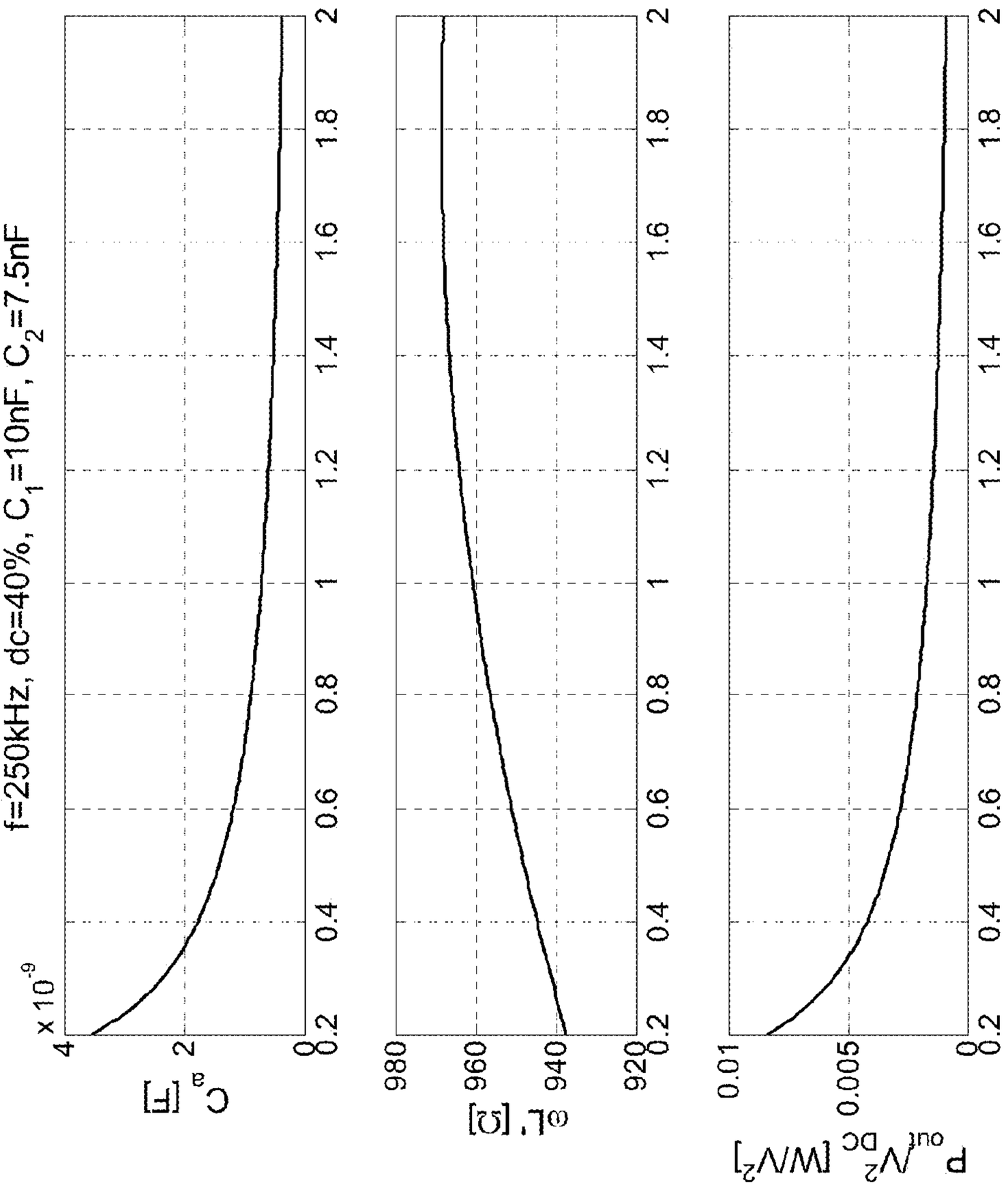


Fig. 11B

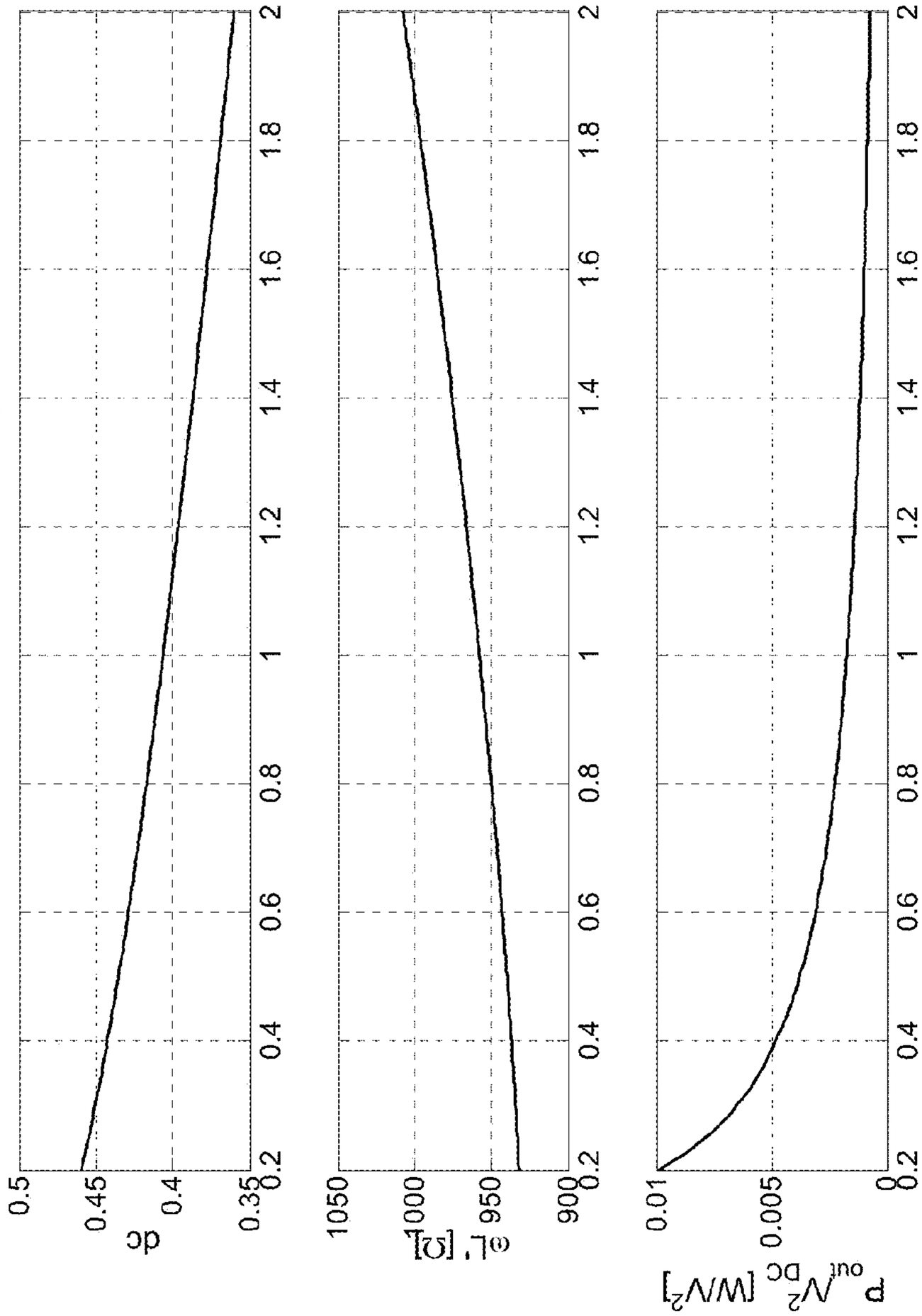


Fig. 11C

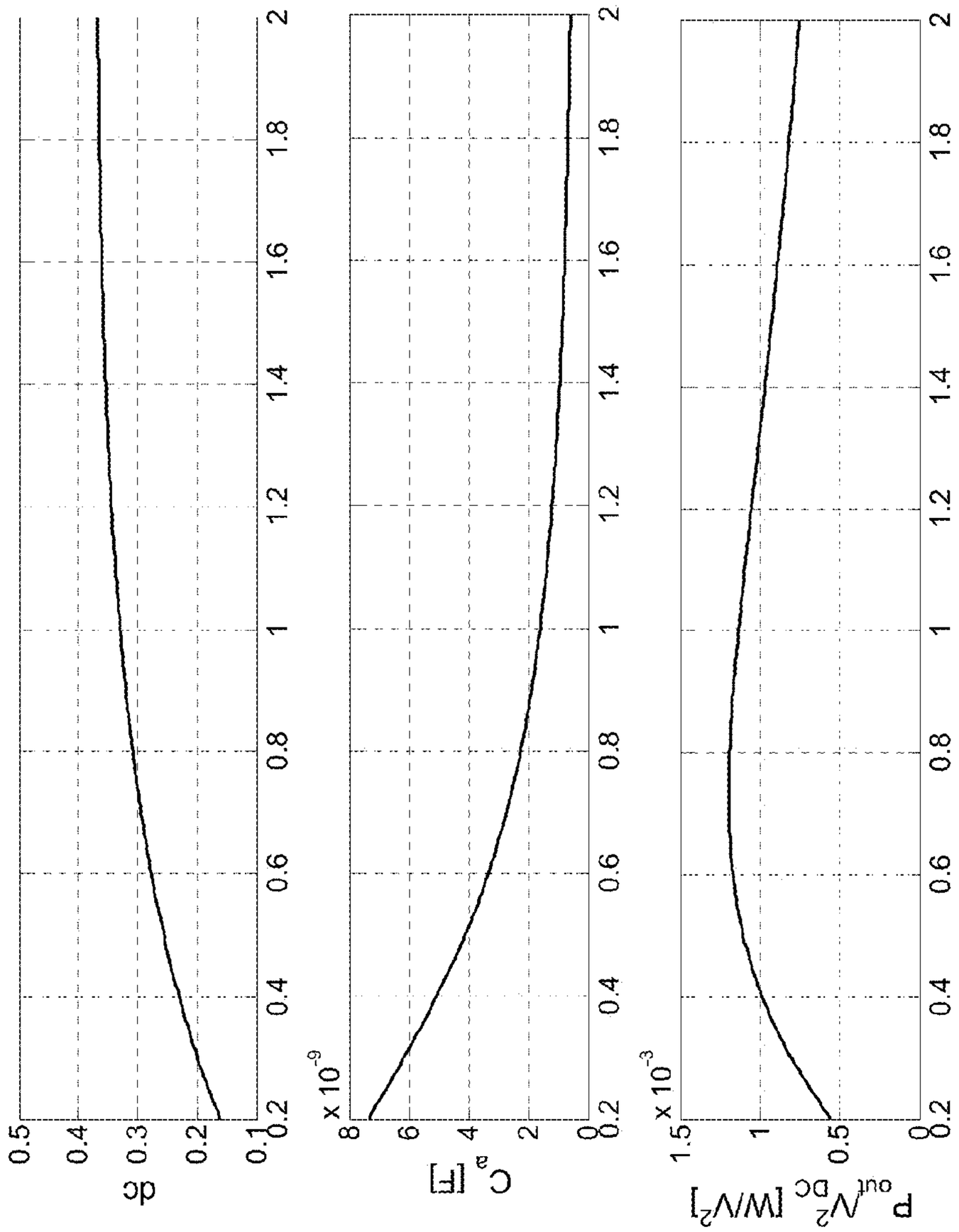

f=250kHz, C1=10nF, C2=7.5nF, ωL'=1000Ω
dc
Ca [F]
Pout/V2DC [W/V2]
R [Ω], L=100μH

Fig. 12

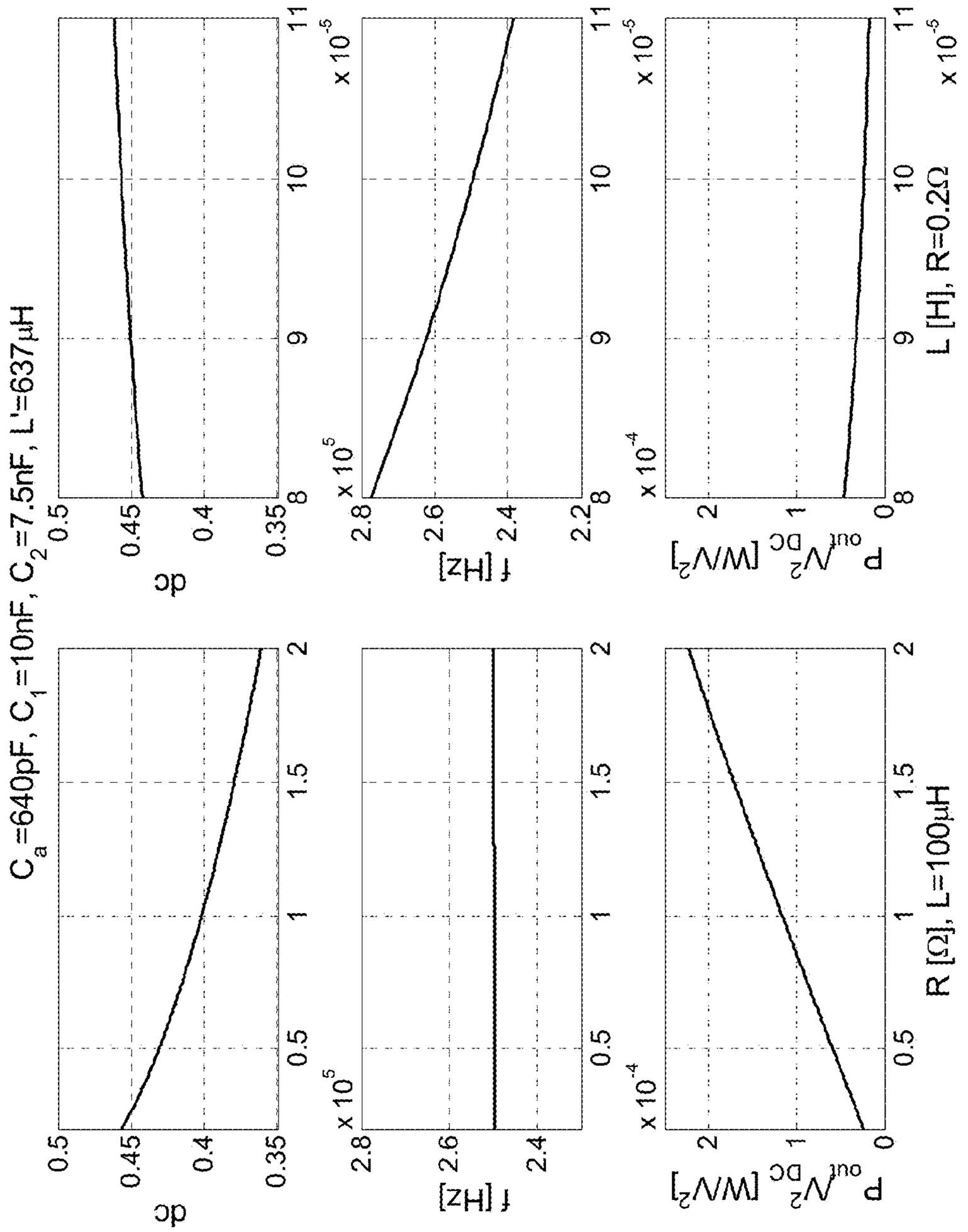

C_a=640pF, C_1=10nF, C_2=7.5nF, L'=637µH
dc
f [Hz]
P_{out}/V^2_{DC} [W/V^2]
R [Ω], L=100µH
L [H], R=0.2Ω
x 10^{-5}
x 10^{5}
x 10^{-4}

Fig. 13

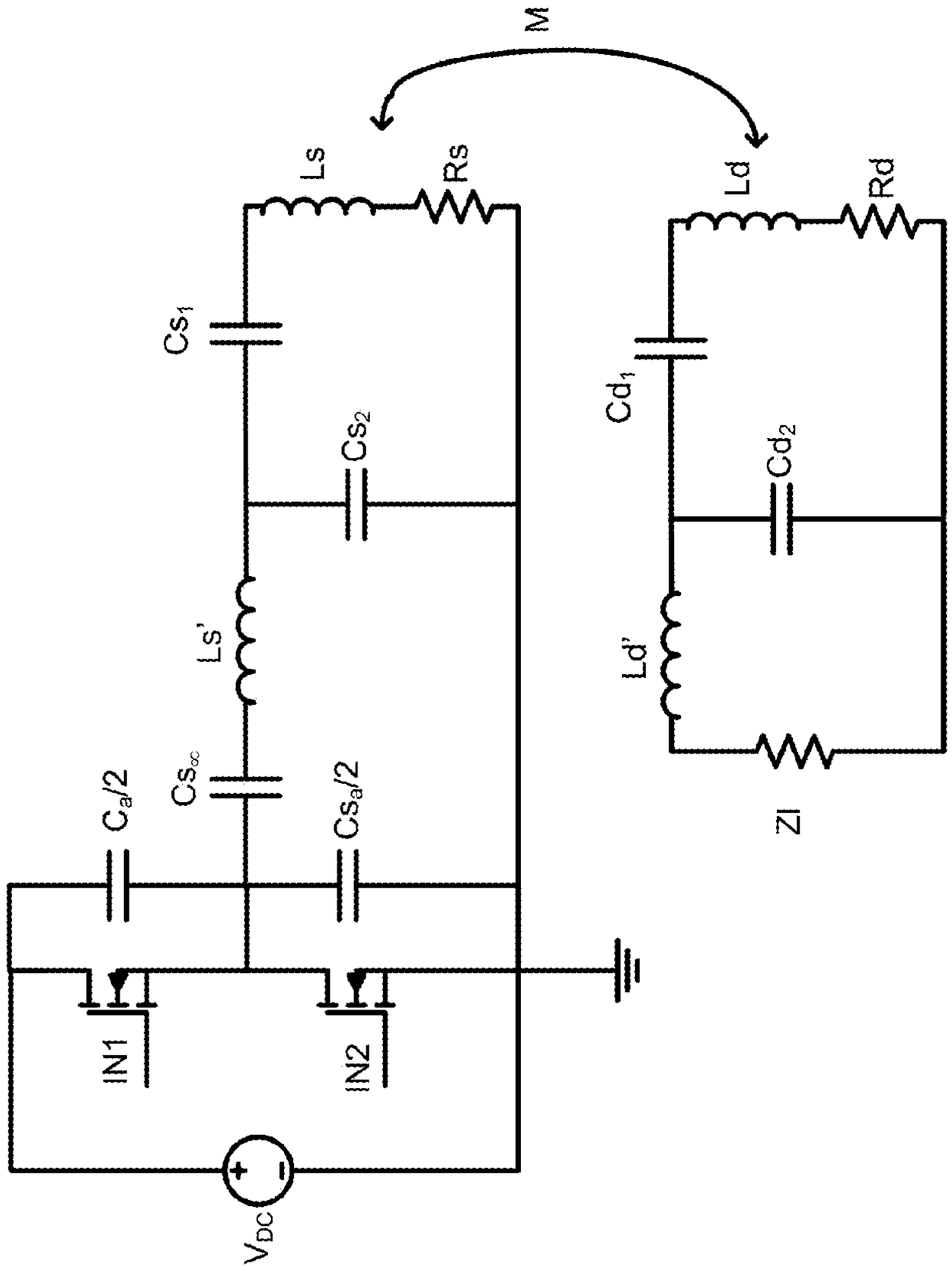


Fig. 14

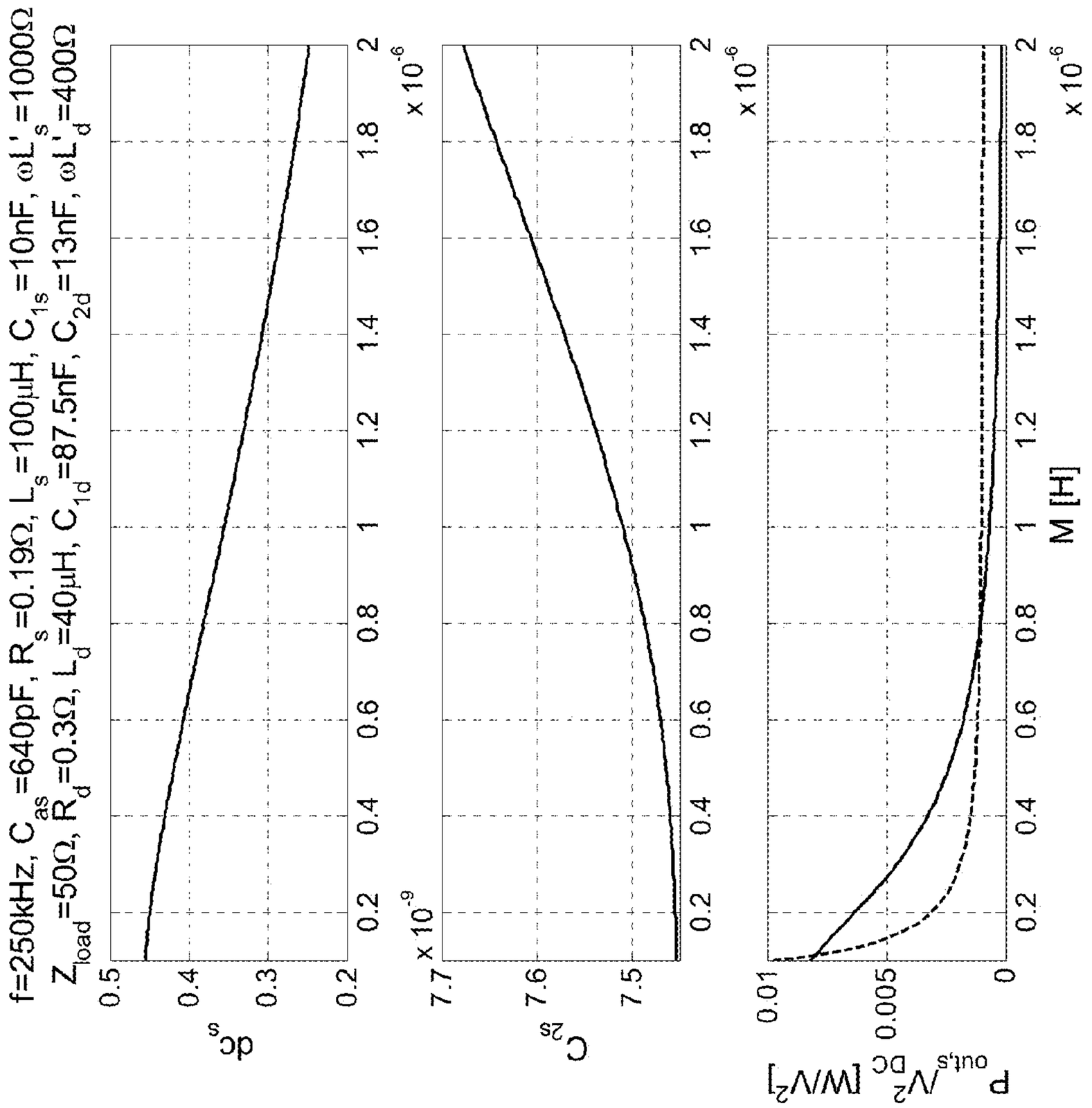

f=250kHz, C_{as}=640pF, R_s=0.19Ω, L_s=100μH, C_{1s}=10nF, ωL'$_s$=1000Ω
Z_{load}=50Ω, R_d=0.3Ω, L_d=40μH, C_{1d}=87.5nF, C_{2d}=13nF, ωL'$_d$=400Ω
dc_s
C_{2s}
$P_{out,s}/V^2_{DC}$ [W/V^2]
x 10^{-6}
x 10^{-9}
M [H]

Fig. 15

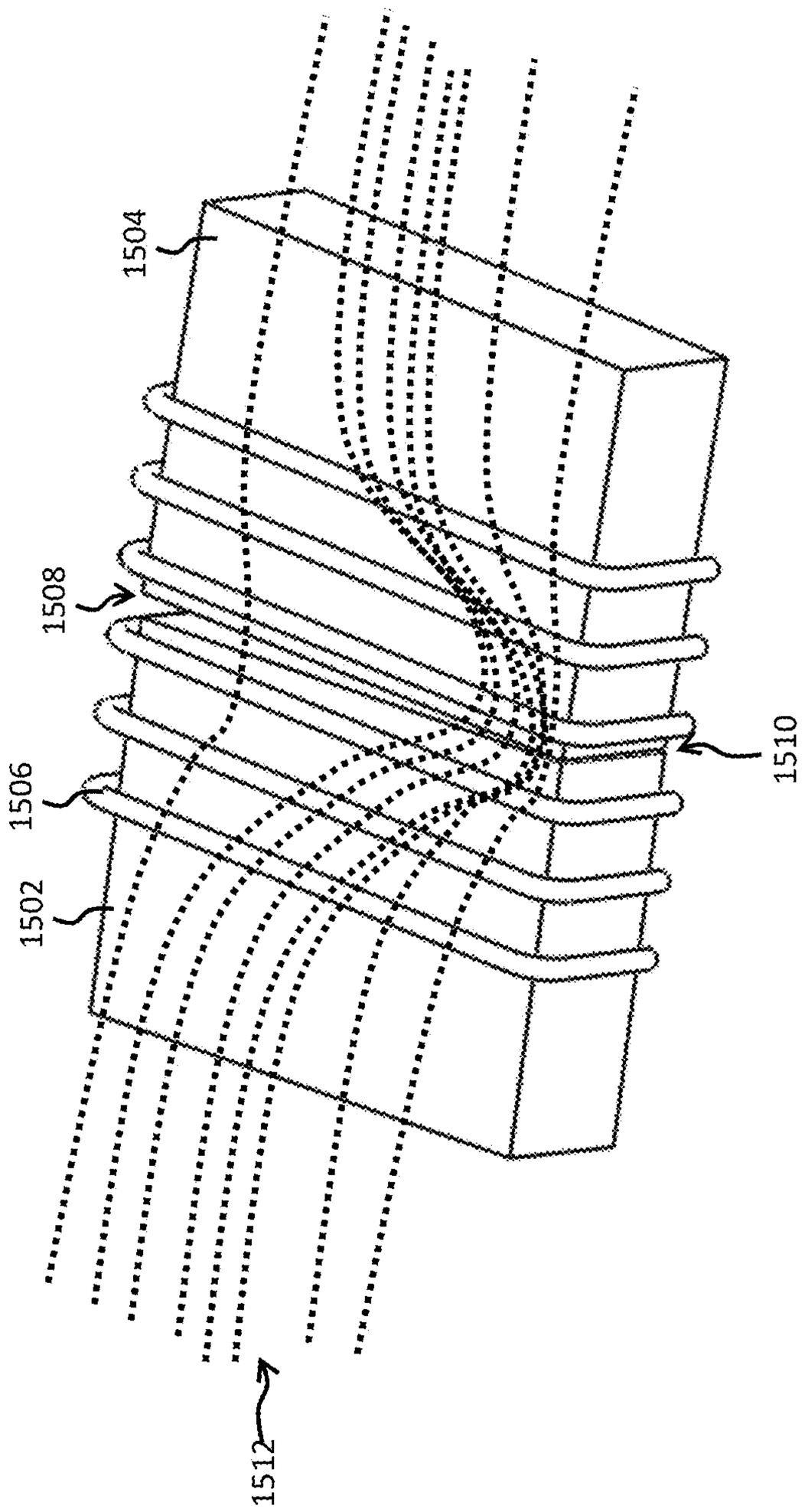
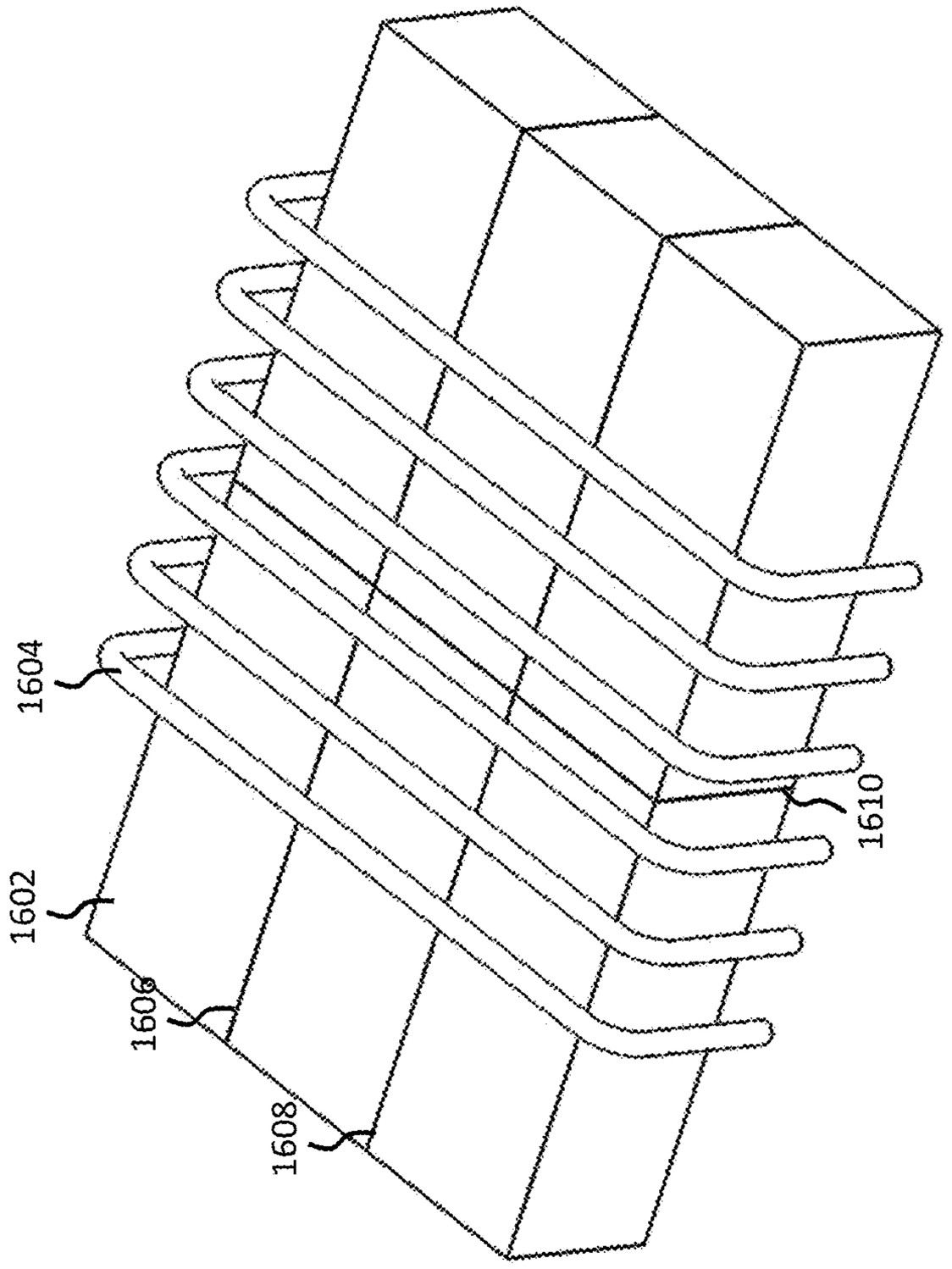


Fig. 16



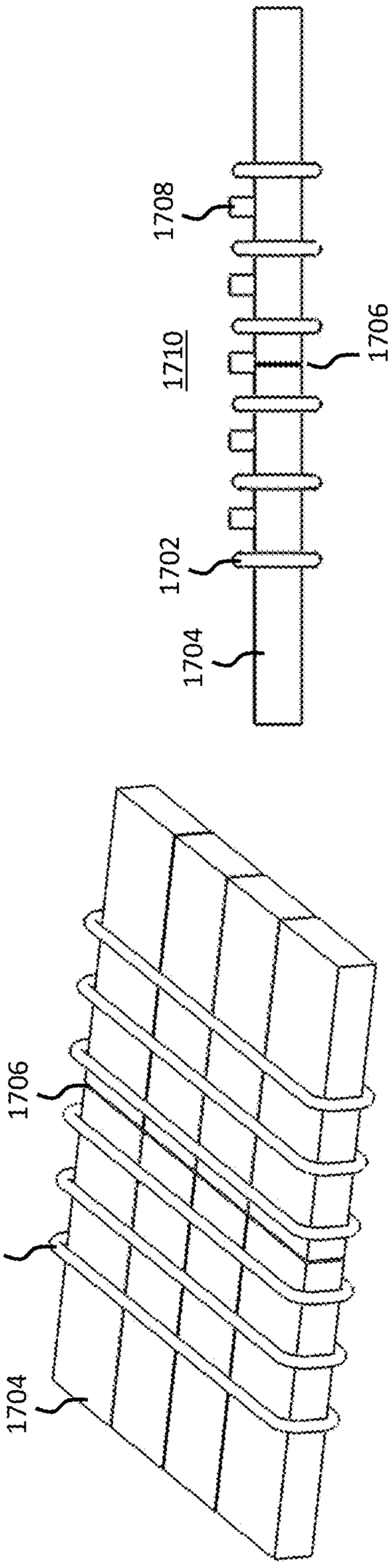


Fig. 17A

Fig. 17B

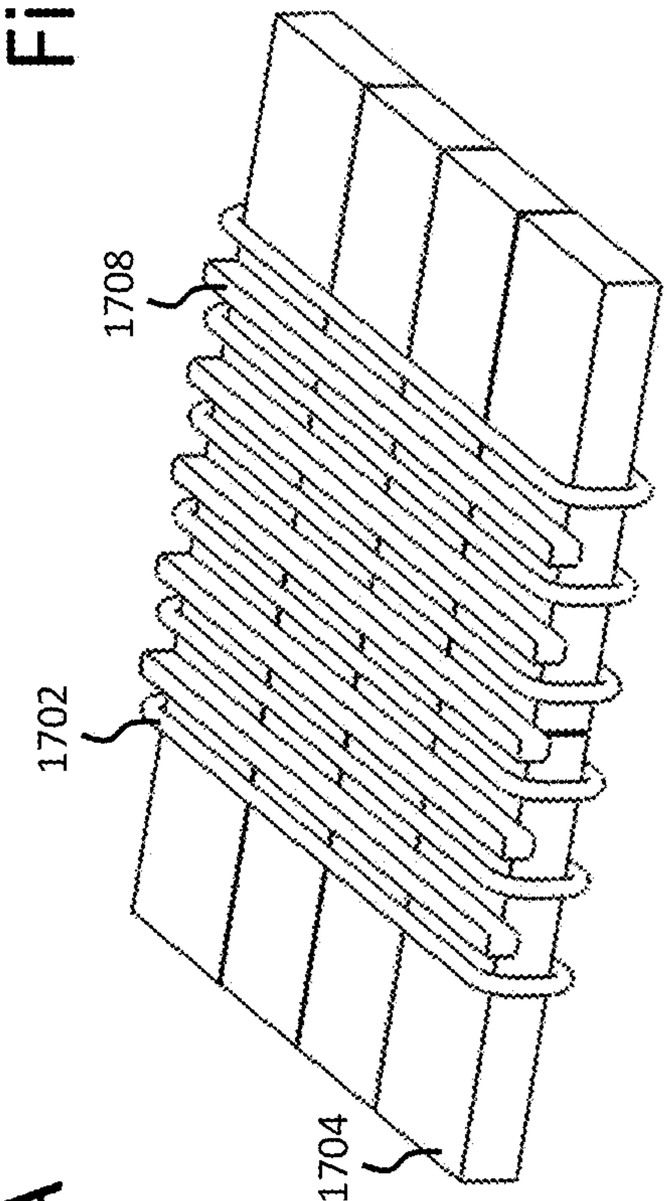


Fig. 17C

Fig. 18

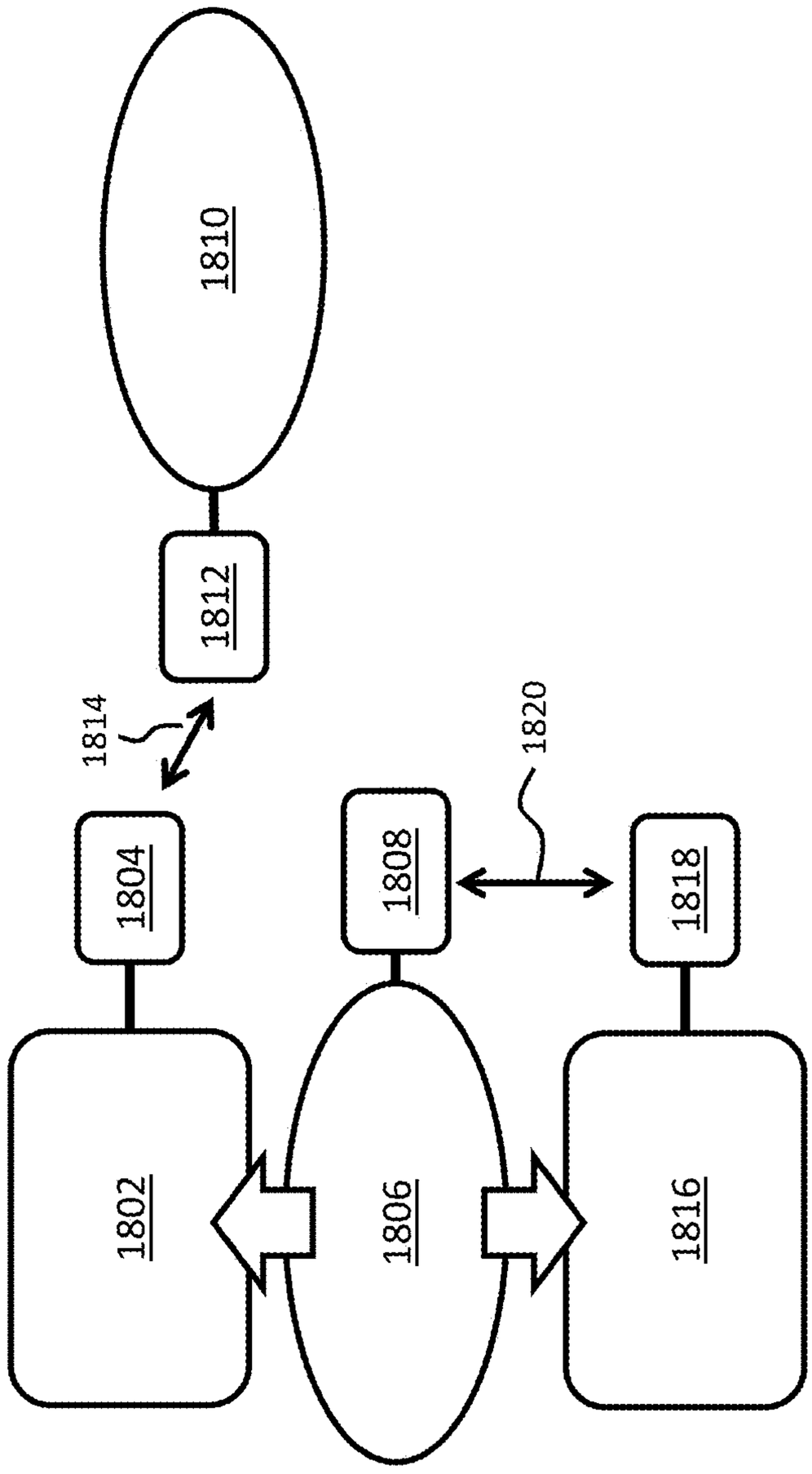


Fig. 19A

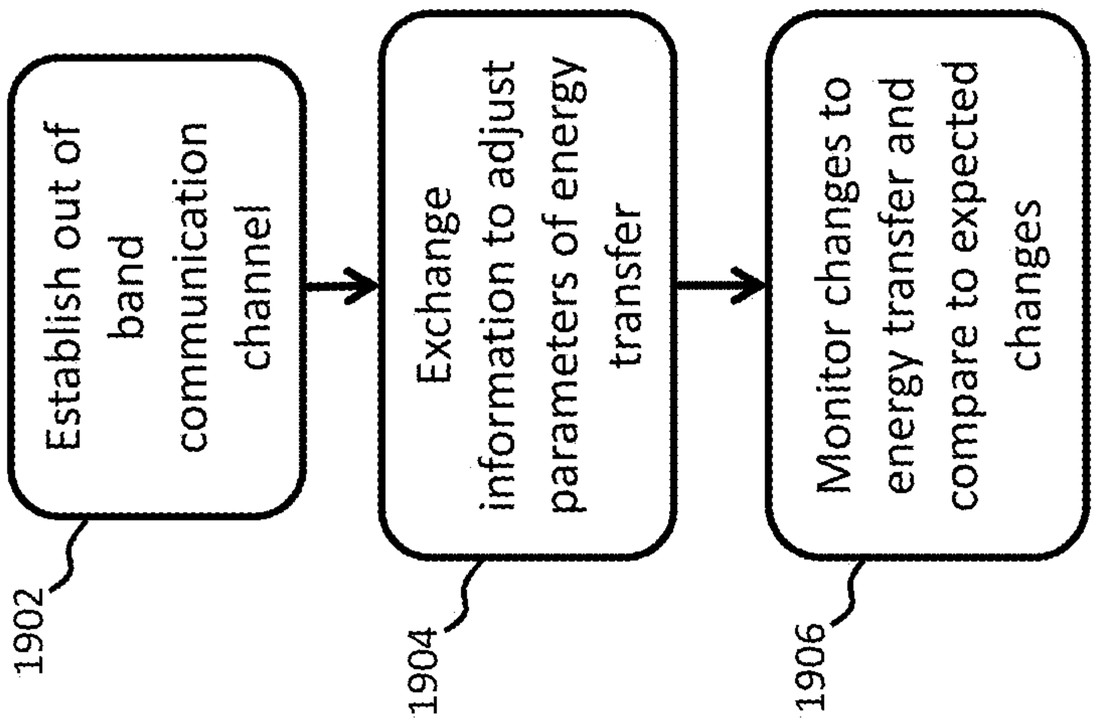


Fig. 19B

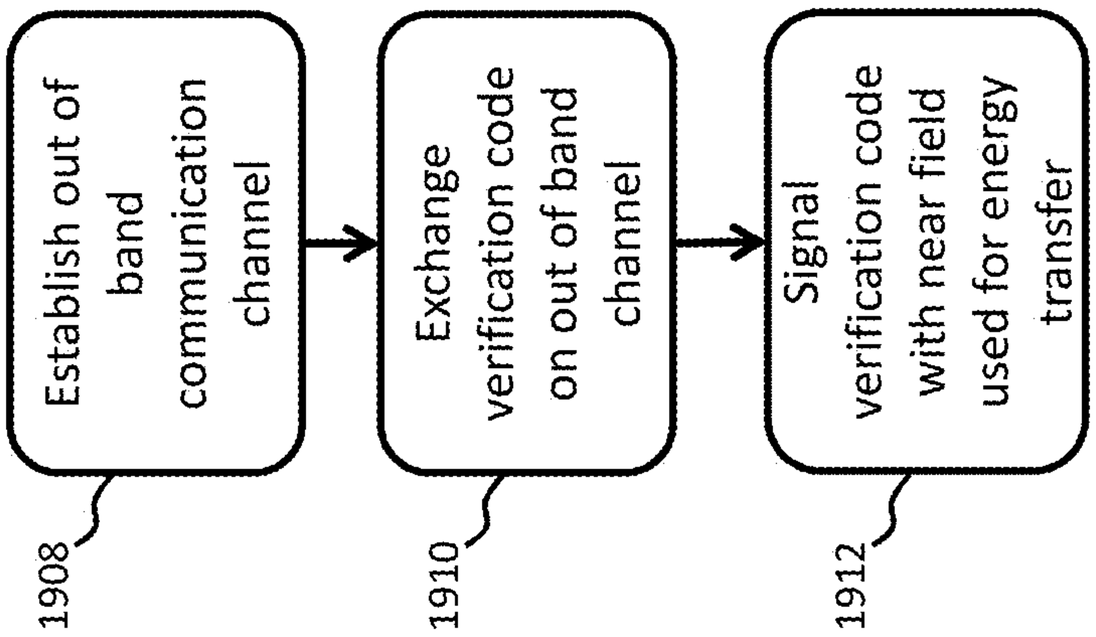


Fig. 20

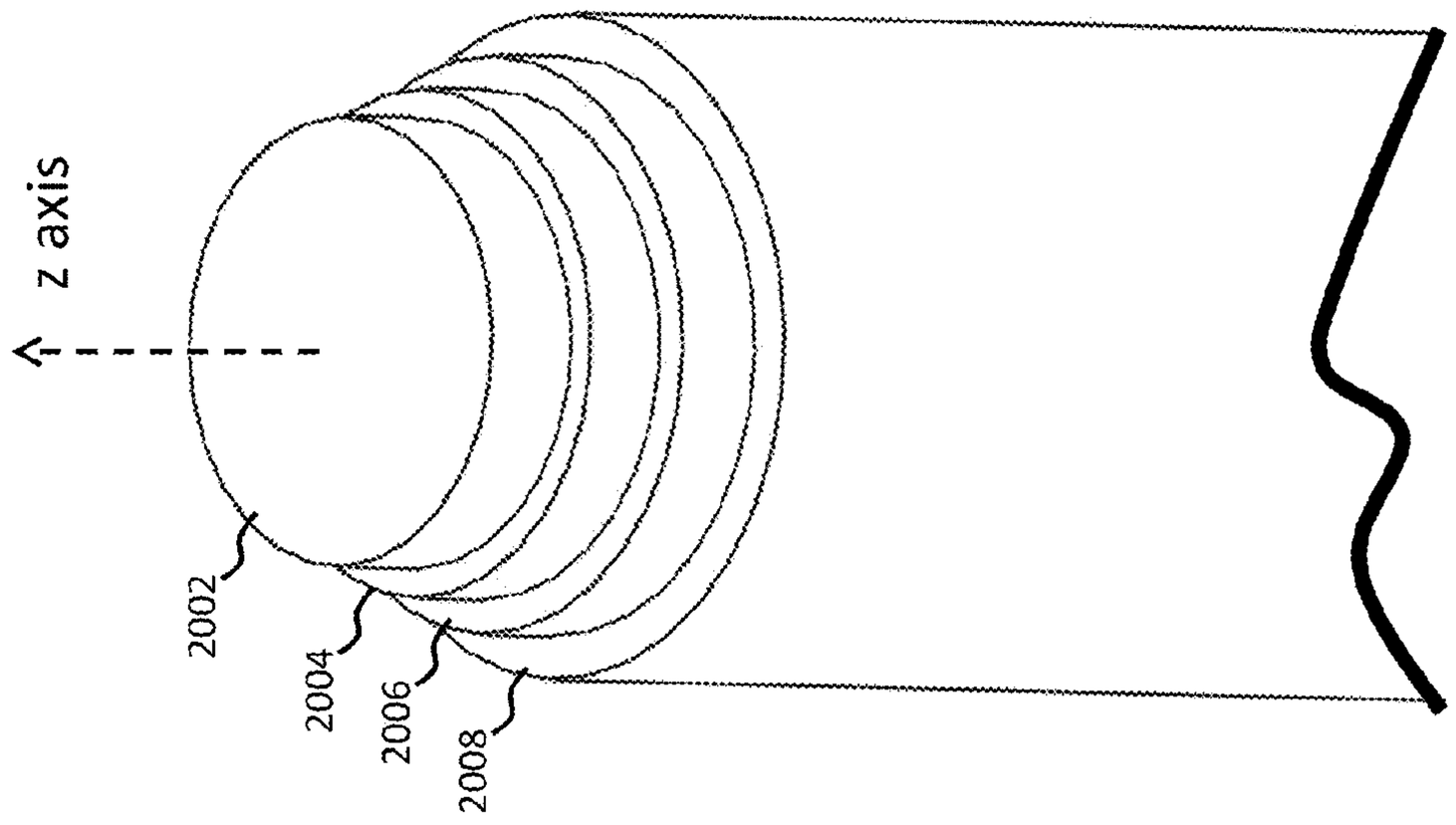


Fig. 21

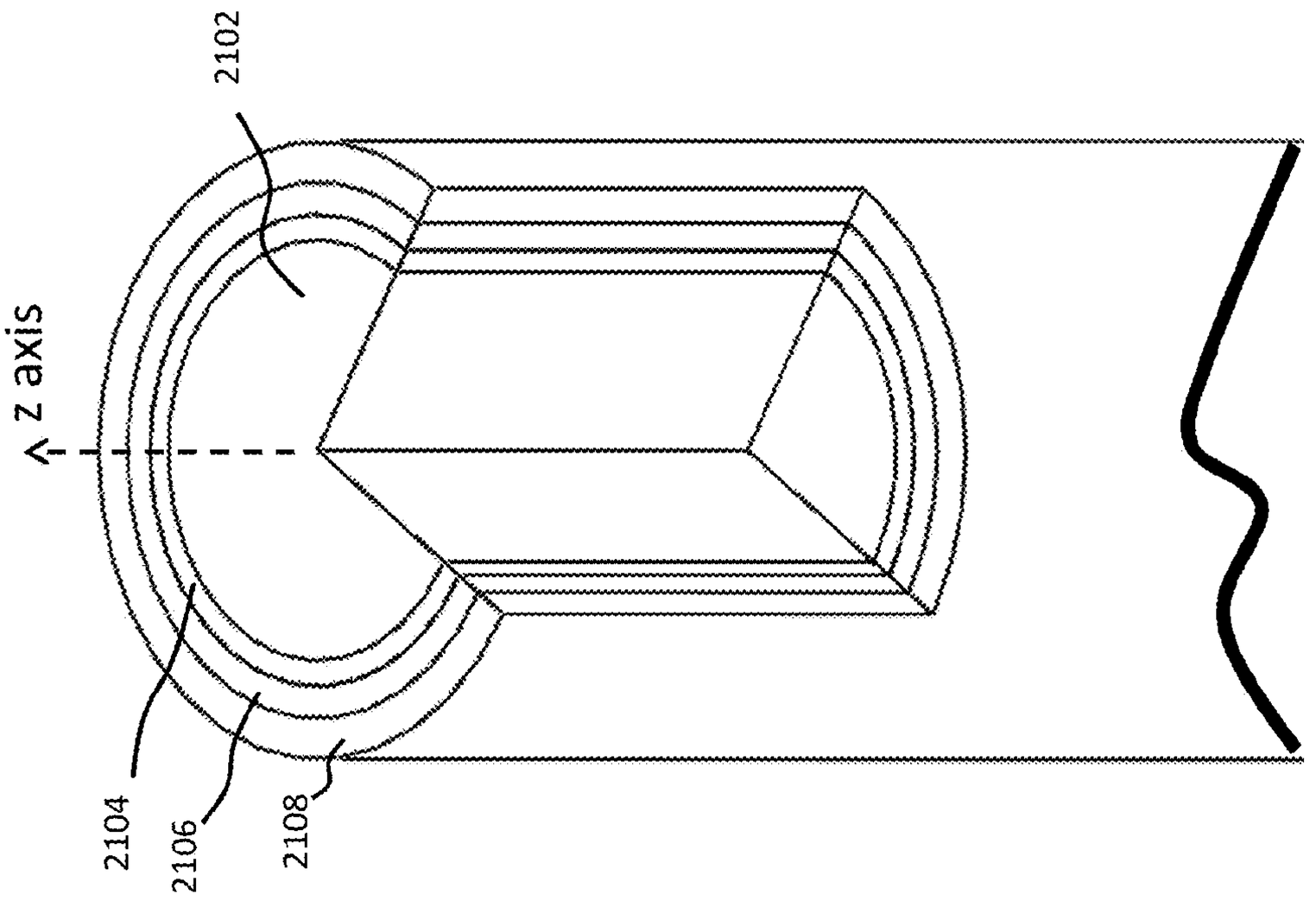


Fig. 22

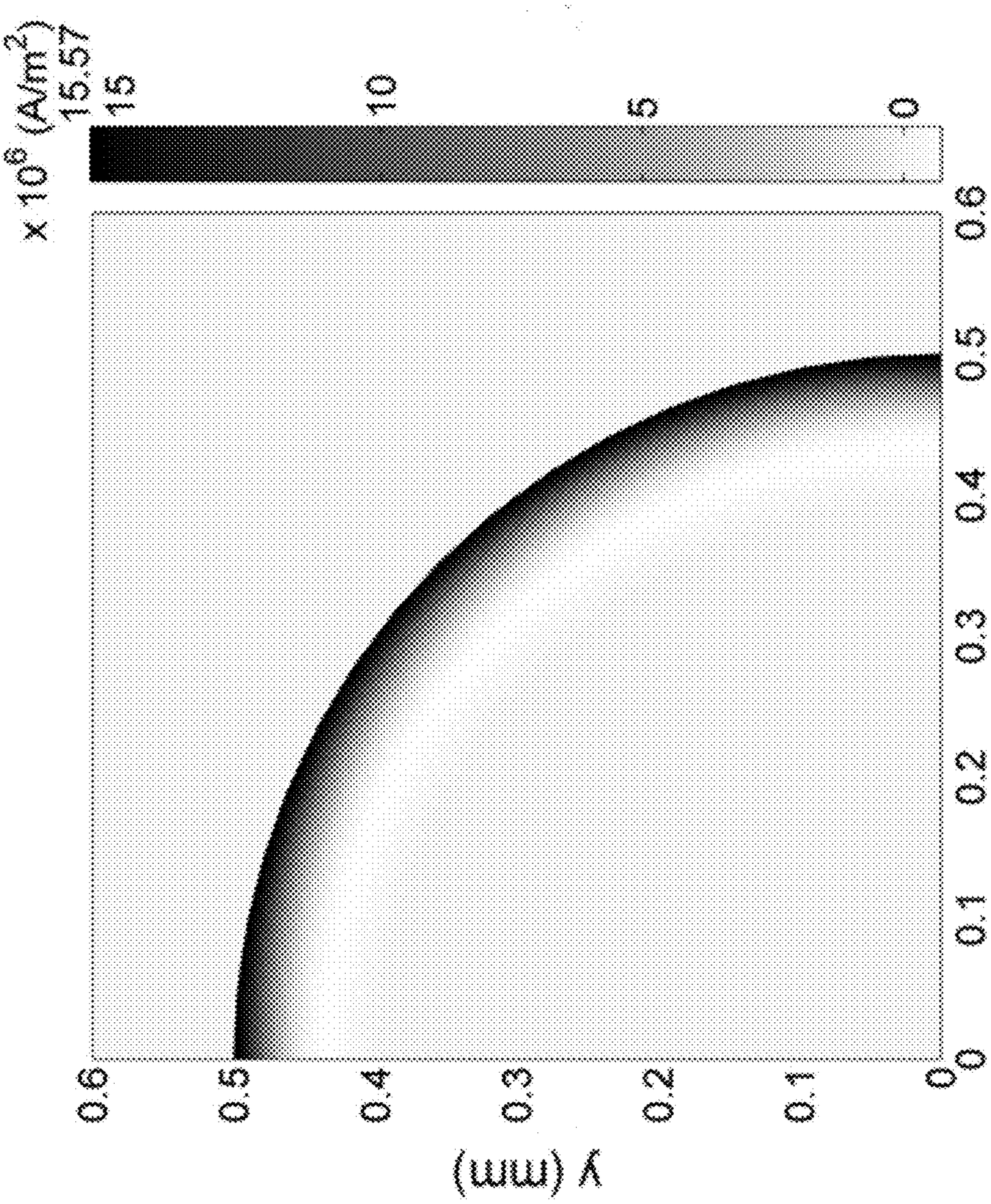
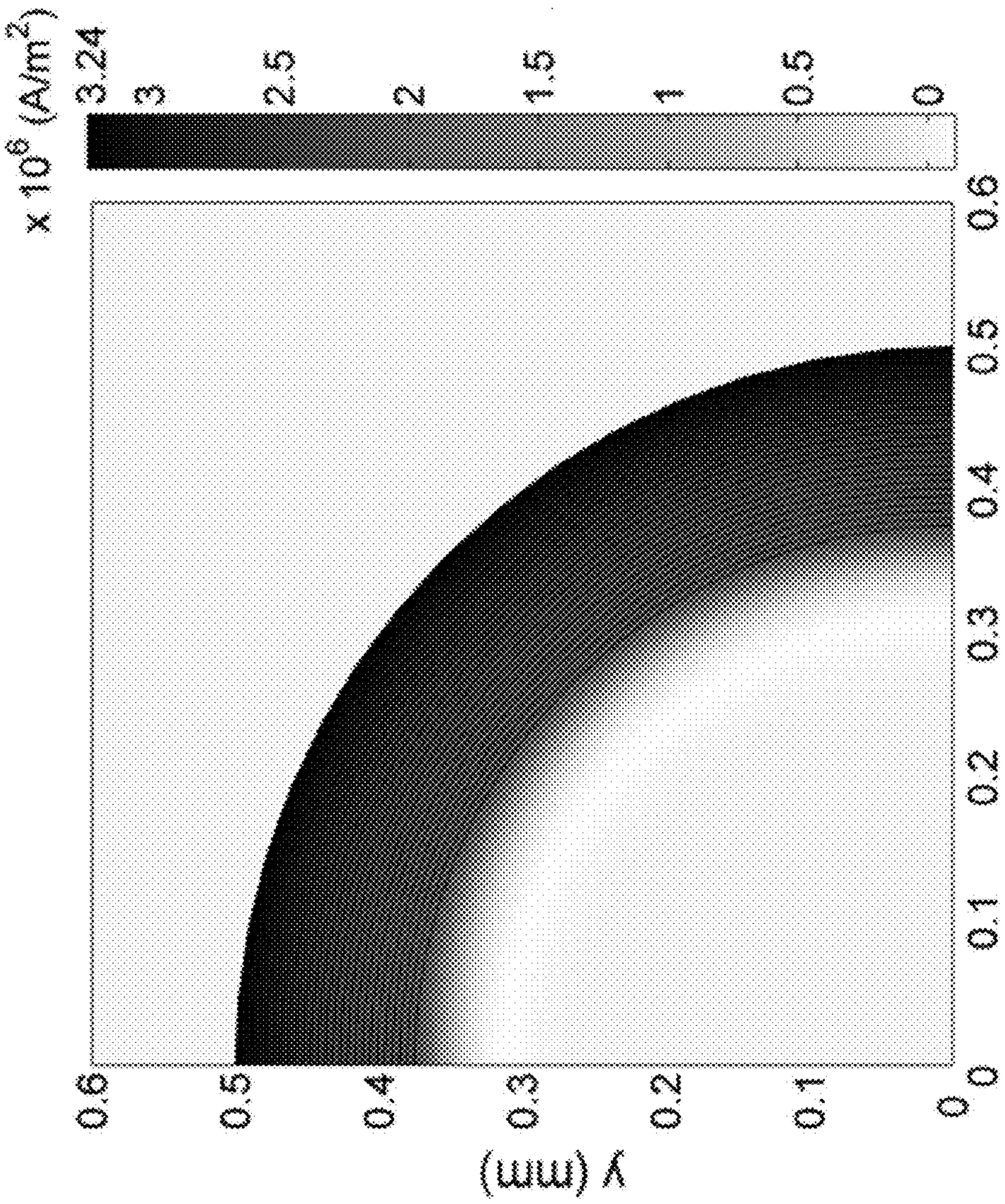


Fig. 23


10^6 (A/m^2)
3.24
3
2.5
2
1.5
1
0.5
0
x (mm)
0.1
0.2
0.3
0.4
0.5
0.6
y (mm)
0.6
0.5
0.4
0.3
0.2
0.1
0

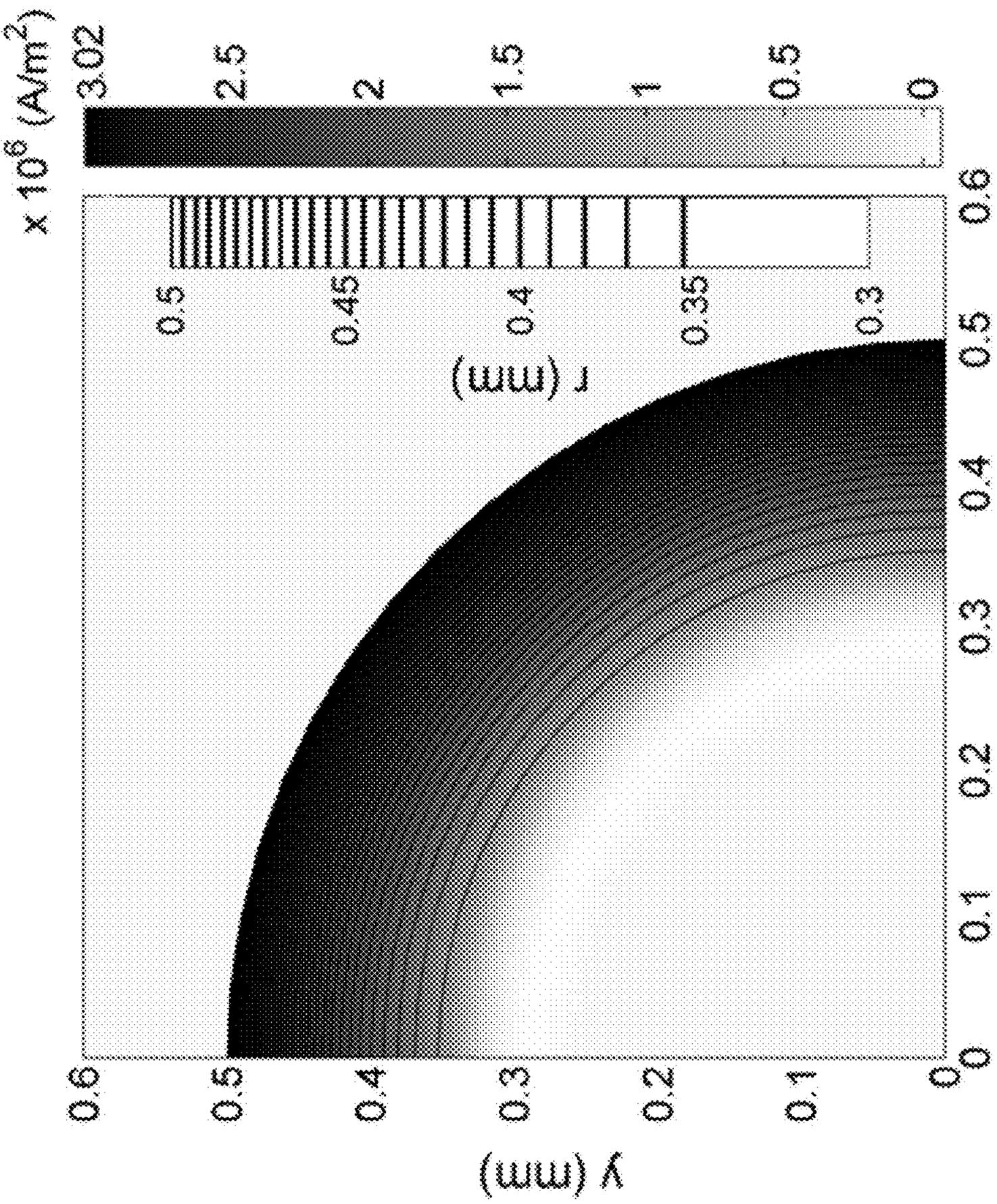

x 10^6 (A/m^2)
3.02
2.5
2
1.5
1
0.5
0
r (mm)
0.5
0.45
0.4
0.35
0.3
x (mm)
0.1
0.2
0.3
0.4
0.5
0.6
y (mm)
0.6
0.5
0.4
0.3
0.2
0.1
0

Fig. 24

Fig. 25

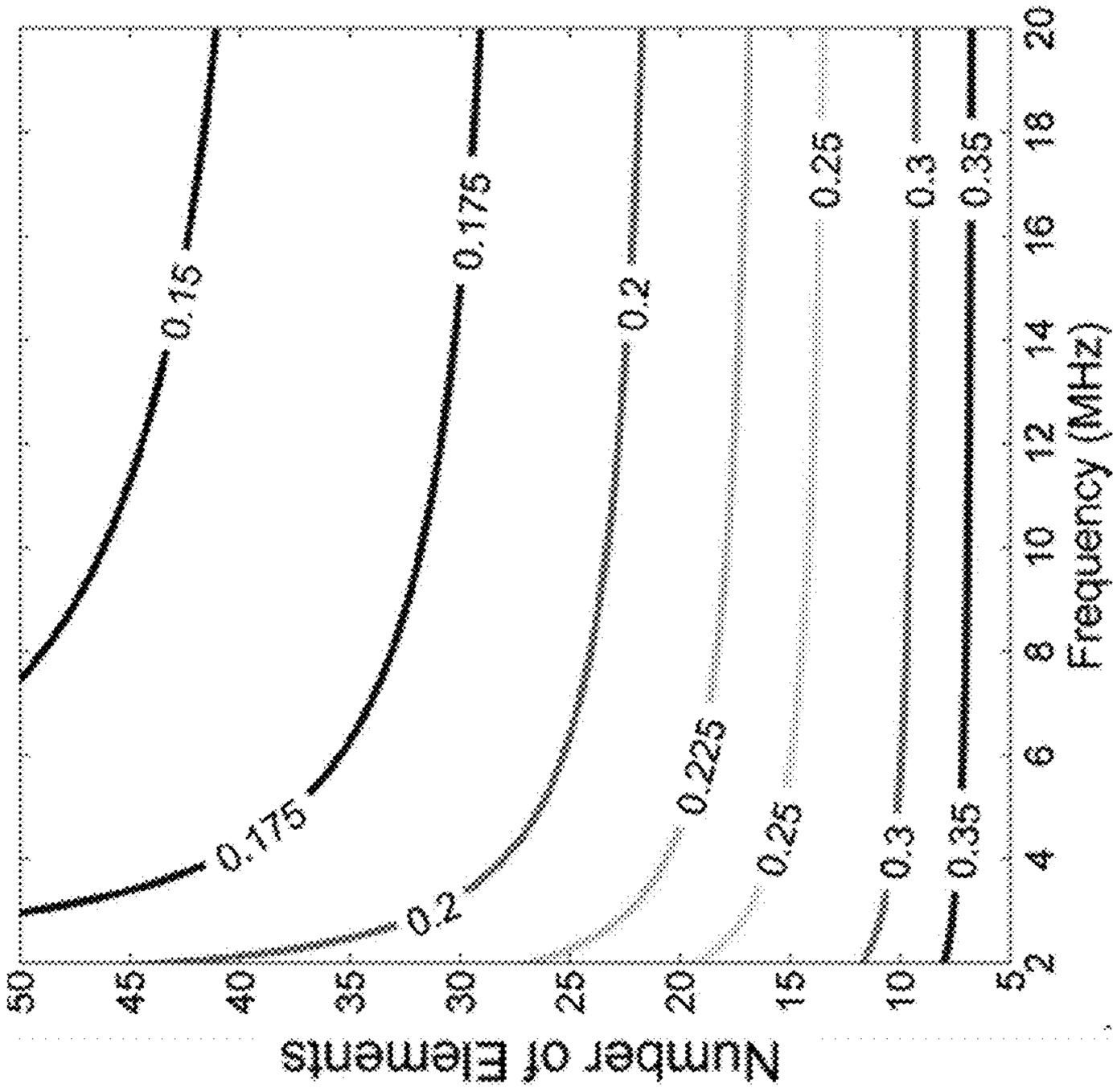


Fig. 26

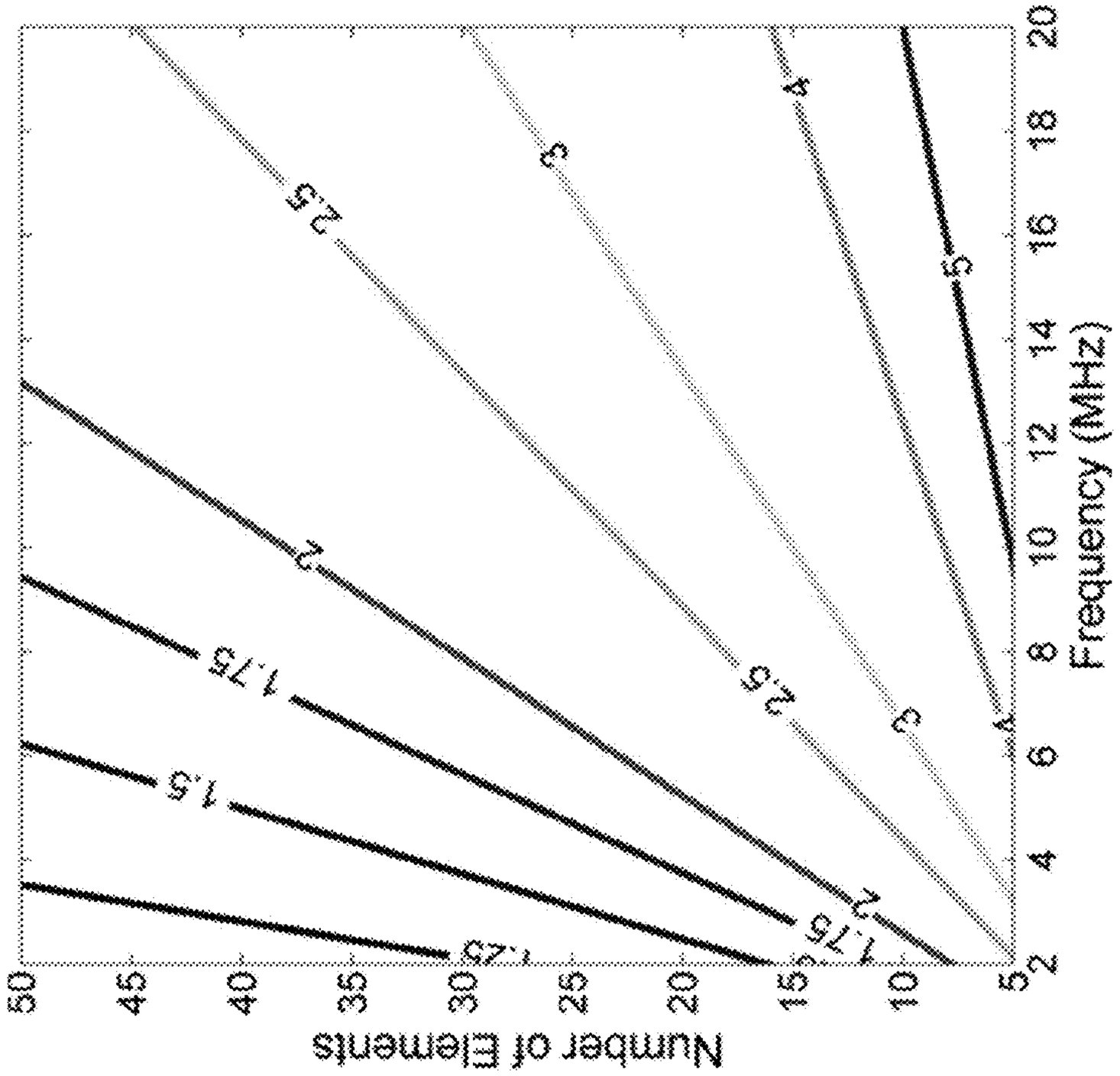

Frequency (MHz)
Number of Elements
2
4
6
8
10
12
14
16
18
20
1
2
3
4
5
2.5
2
1.75
1.5
1.25
2.5
2
1.75
3
4
5

Fig. 27

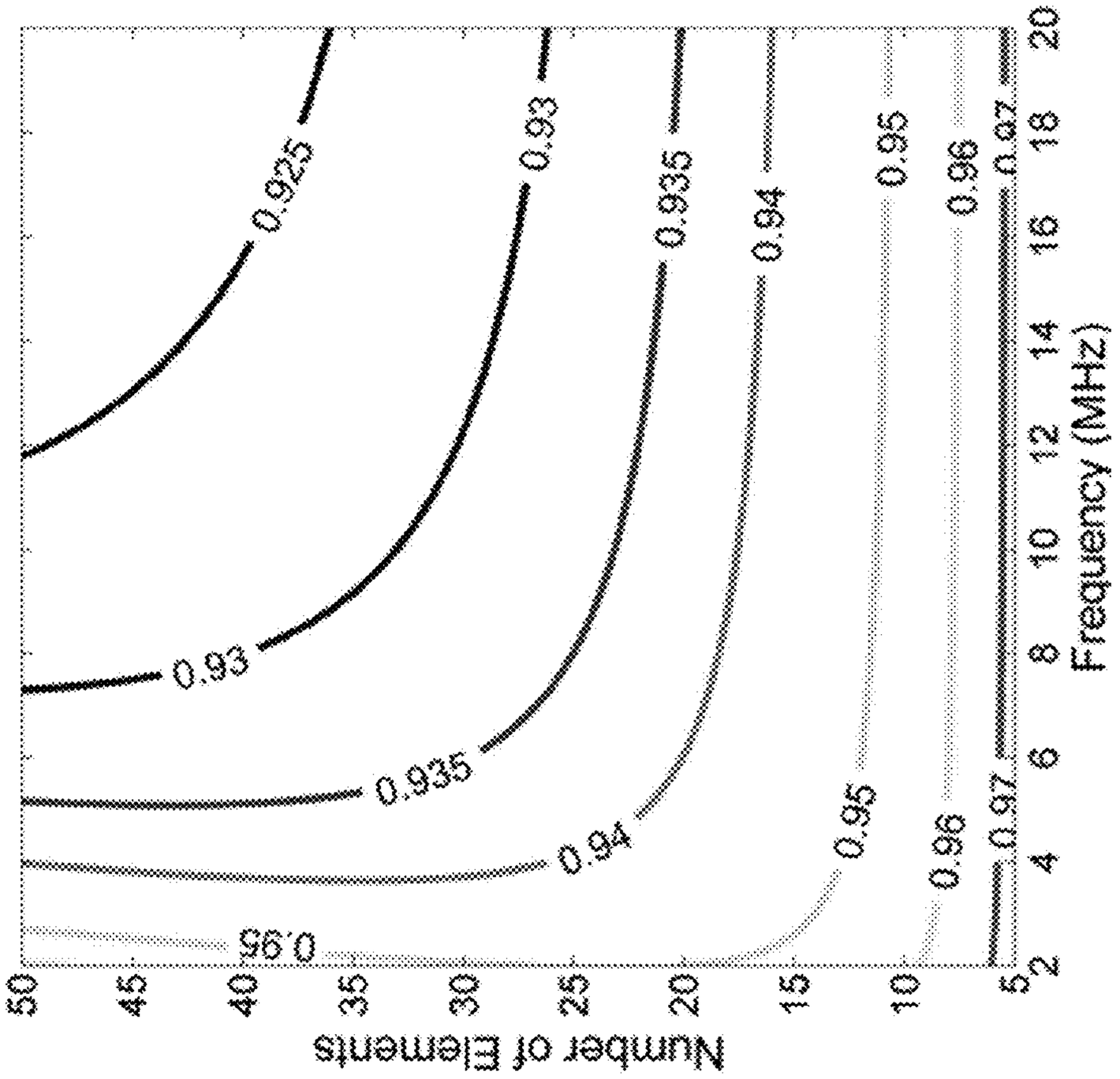
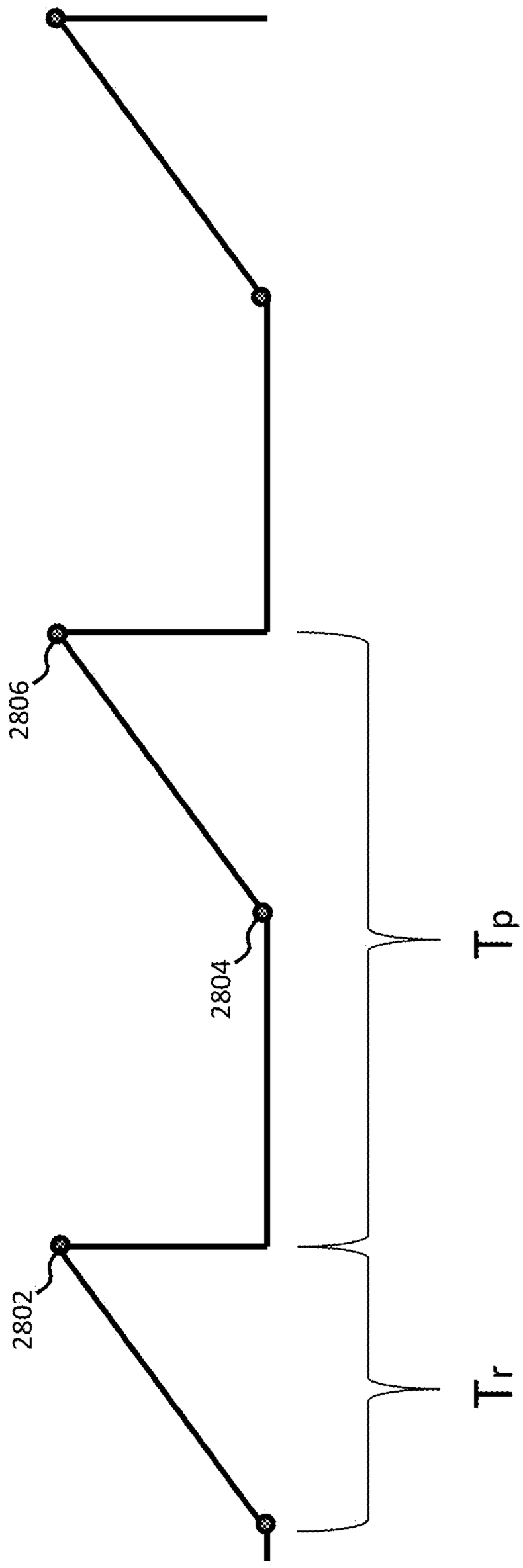

0.925
0.93
0.935
0.94
0.95
0.96
0.97
Frequency (MHz)
Number of Elements

Fig. 28



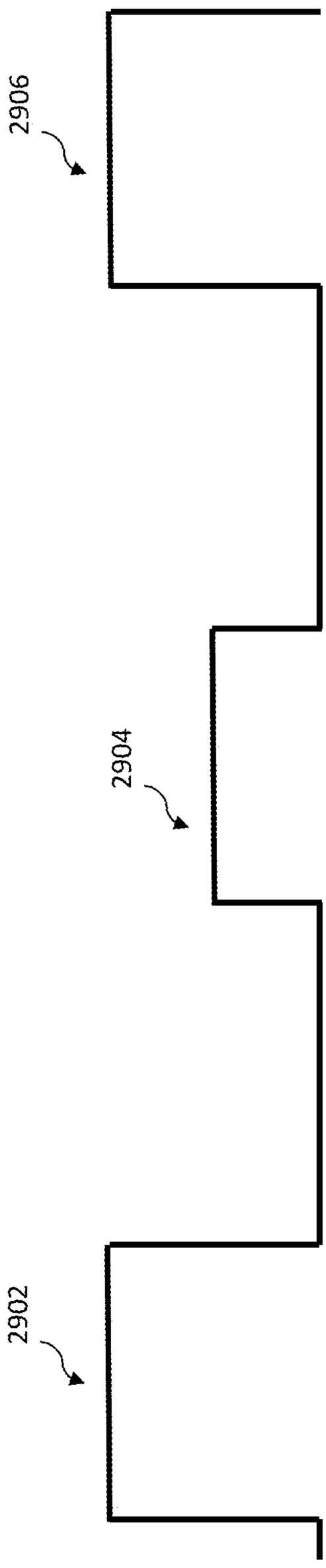


Fig. 29A

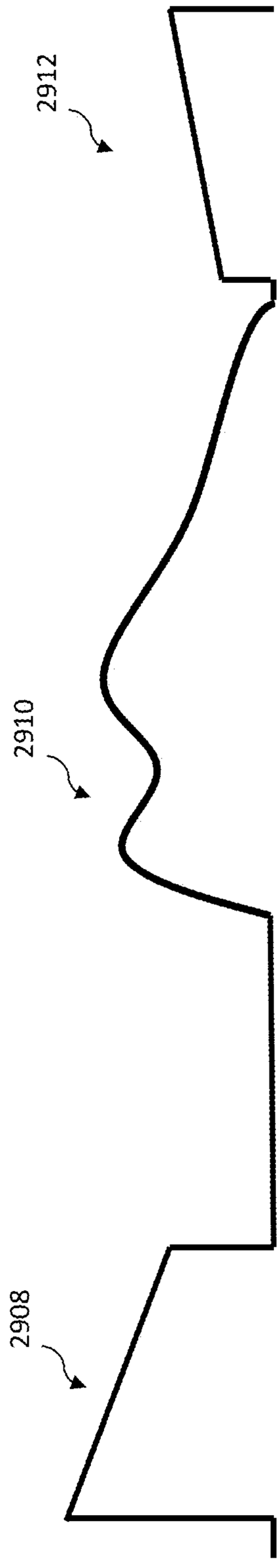


Fig. 29B

Fig. 30

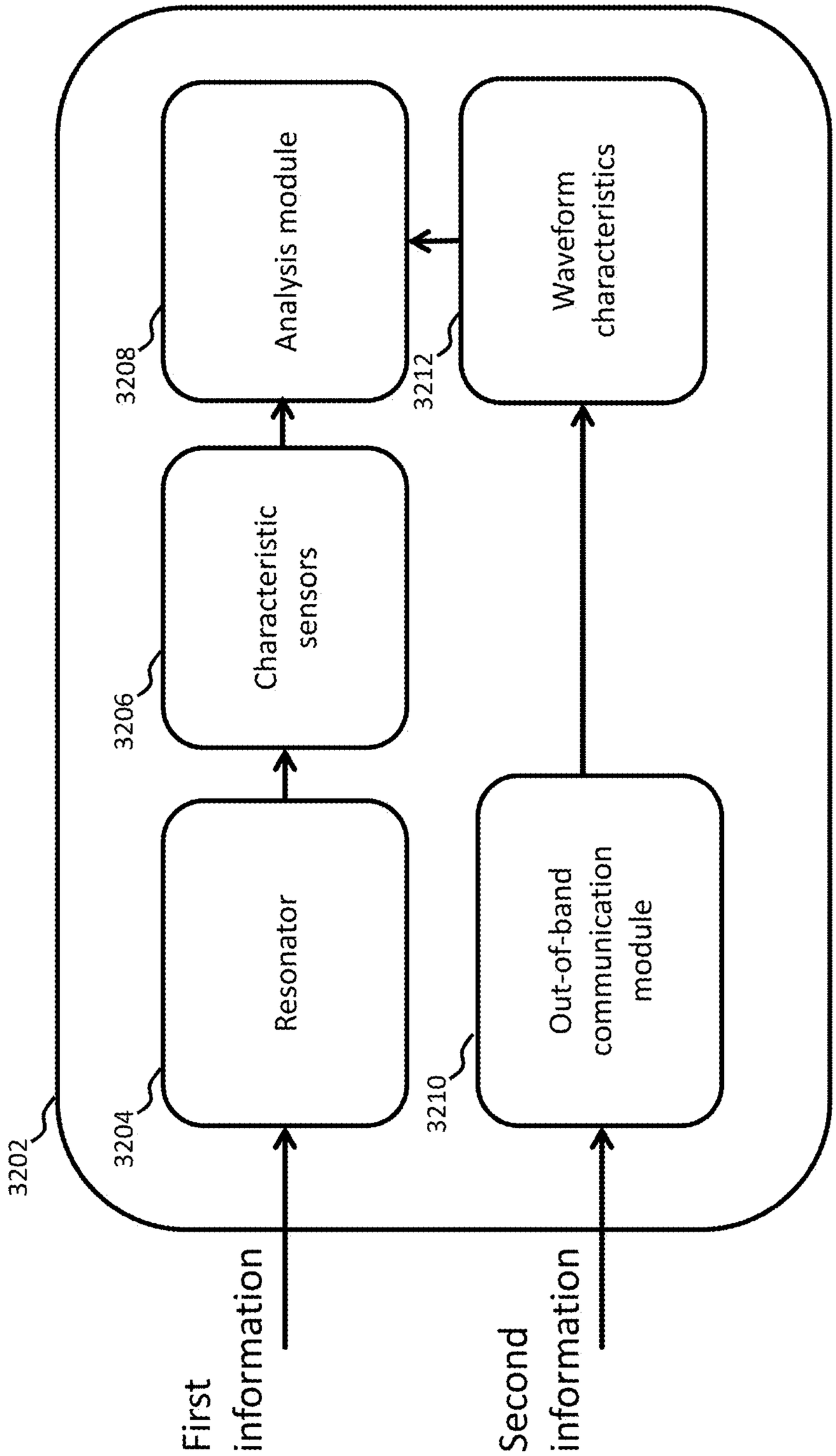

3202
3204
Resonator
3206
Characteristic sensors
3208
Analysis module
3210
Out-of-band communication module
3212
Waveform characteristics
First information
Second information

Fig. 31

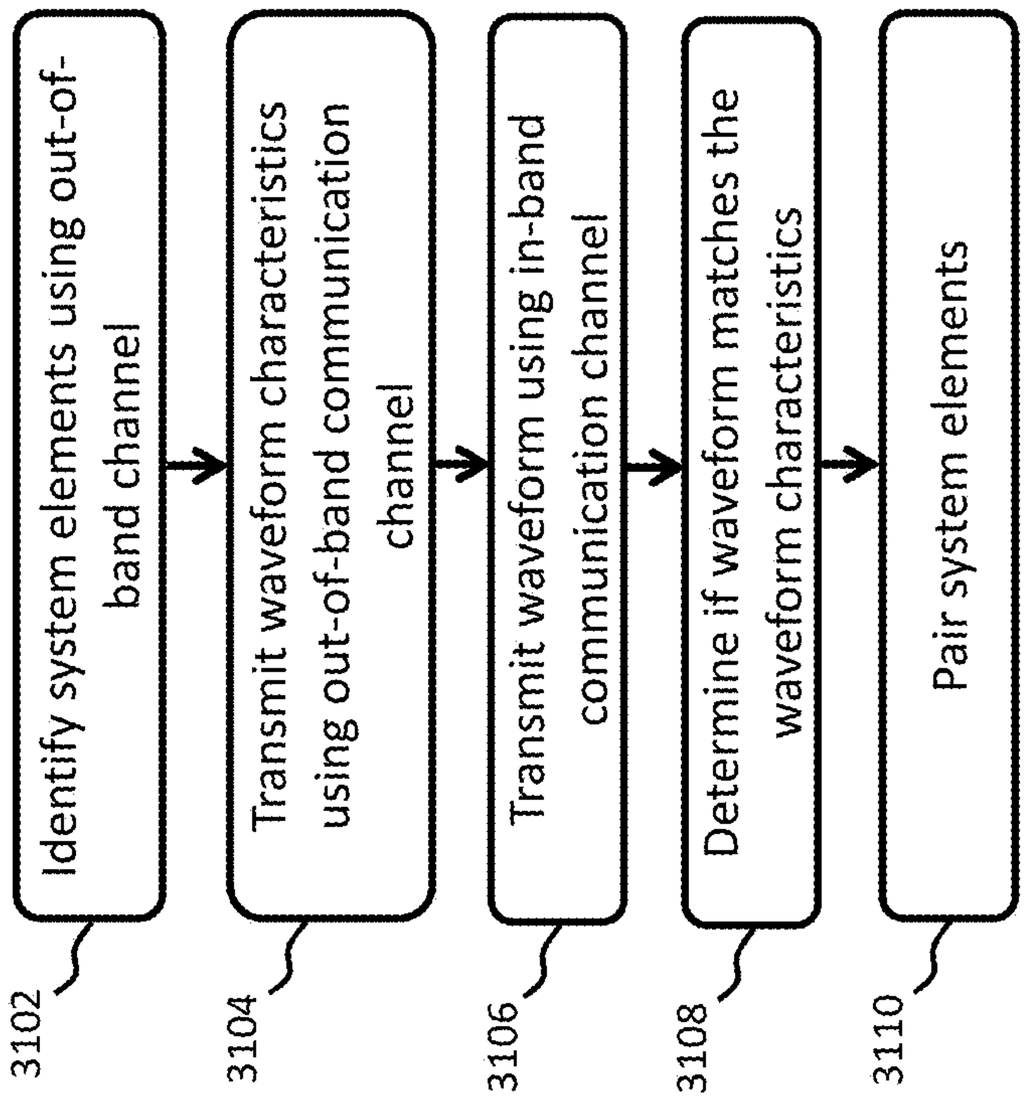

Identify system elements using out-of-band channel
3102
Transmit waveform characteristics using out-of-band communication channel
3104
Transmit waveform using in-band communication channel
3106
Determine if waveform matches the waveform characteristics
3108
Pair system elements
3110

Fig. 32

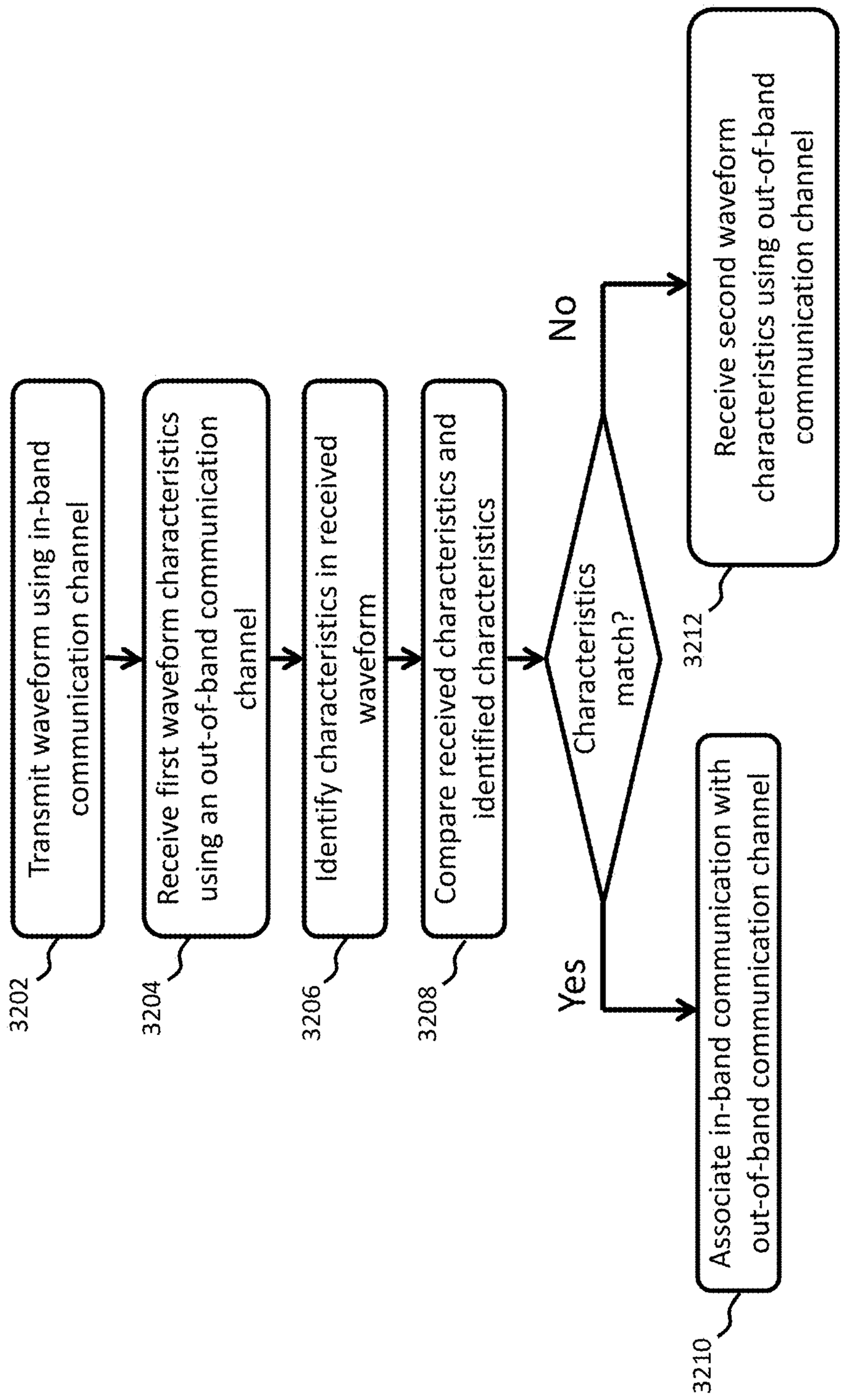

3202
Transmit waveform using in-band communication channel
3204
Receive first waveform characteristics using an out-of-band communication channel
3206
Identify characteristics in received waveform
3208
Compare received characteristics and identified characteristics
Characteristics match?
Yes
No
3210
Associate in-band communication with out-of-band communication channel
3212
Receive second waveform characteristics using communication

Fig. 33

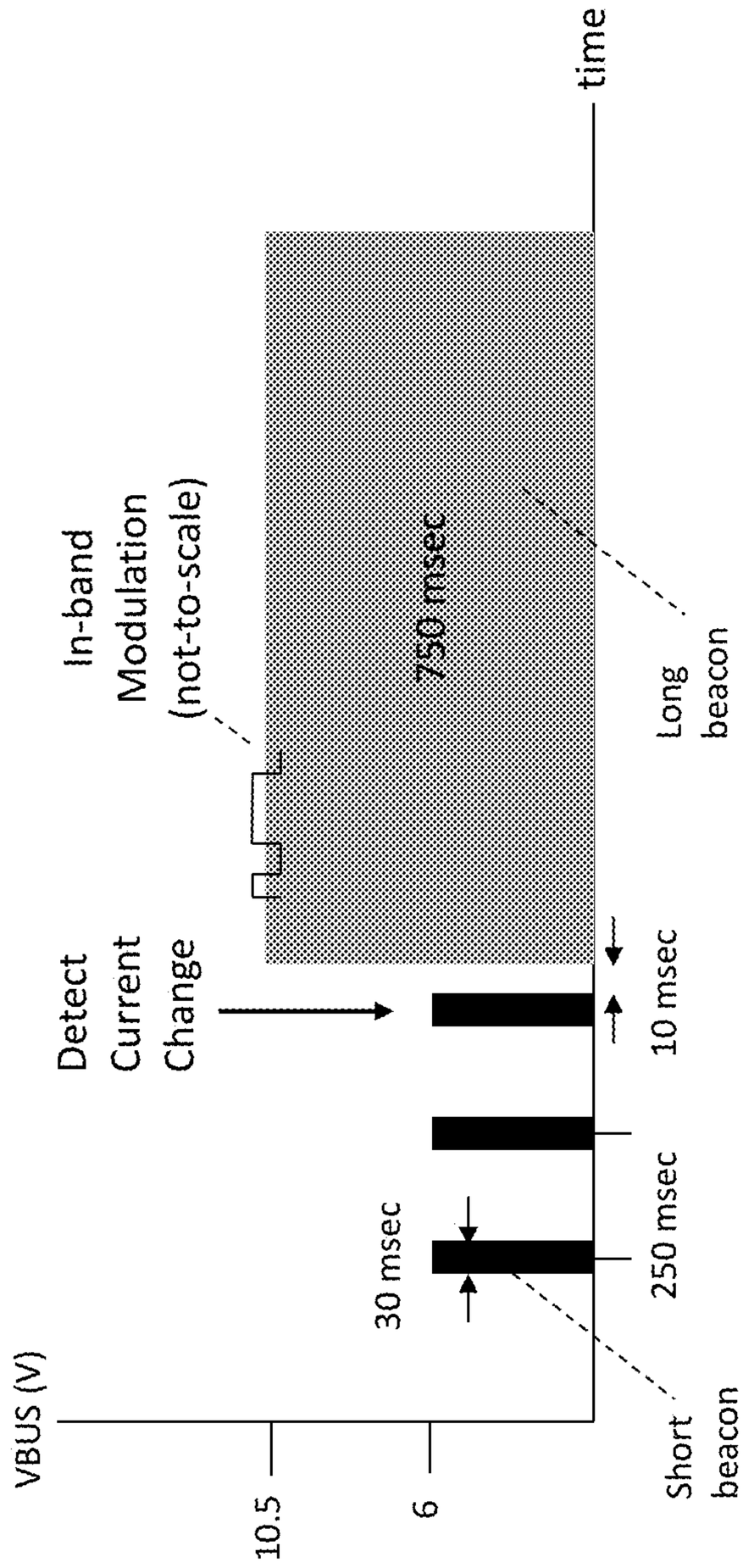

time
In-band Modulation (not-to-scale)
750 msec
Long beacon
Detect Current Change
10 msec
250 msec
30 msec
Short beacon
VBUS (V)
10.5
6

Fig. 34

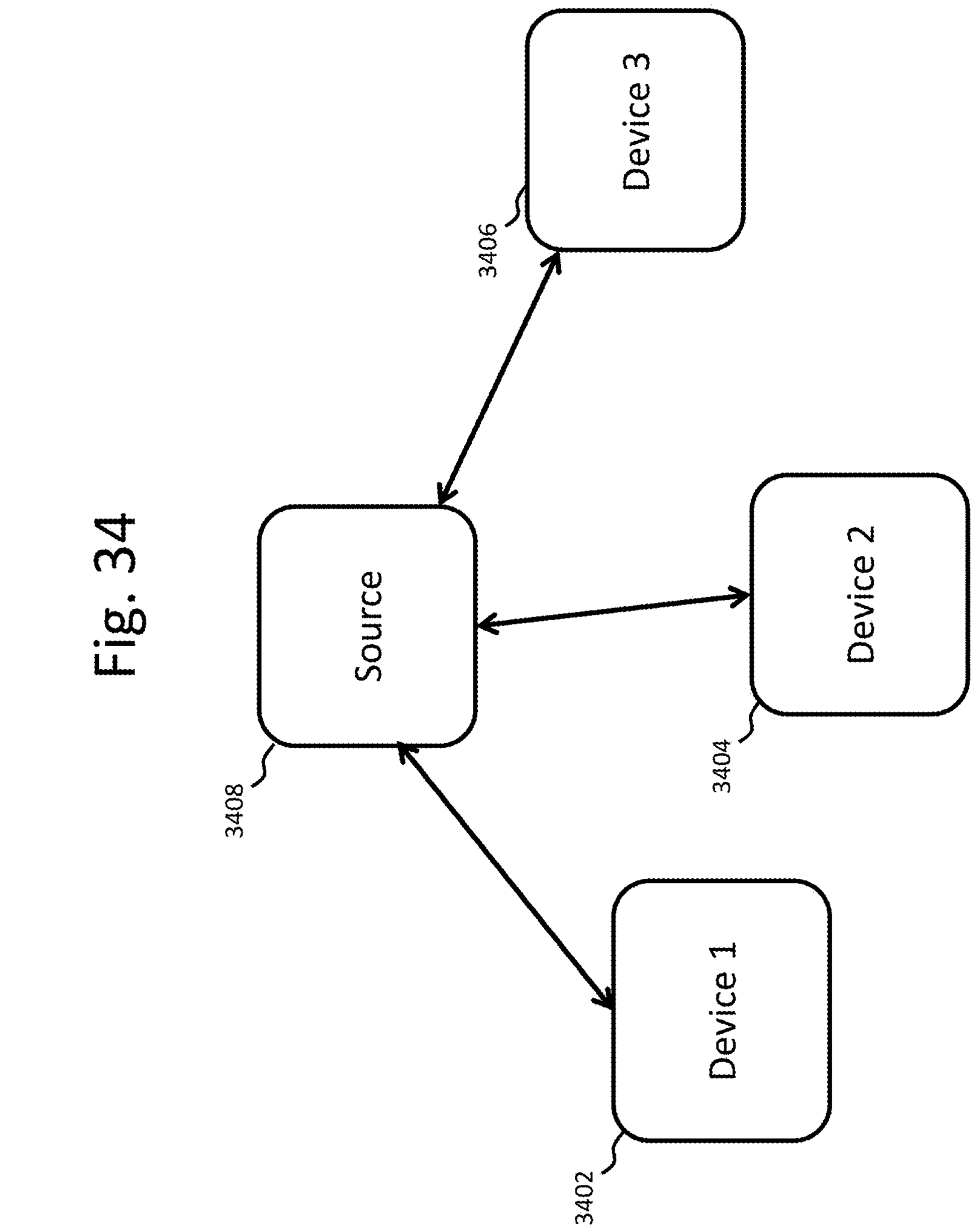


Fig. 35

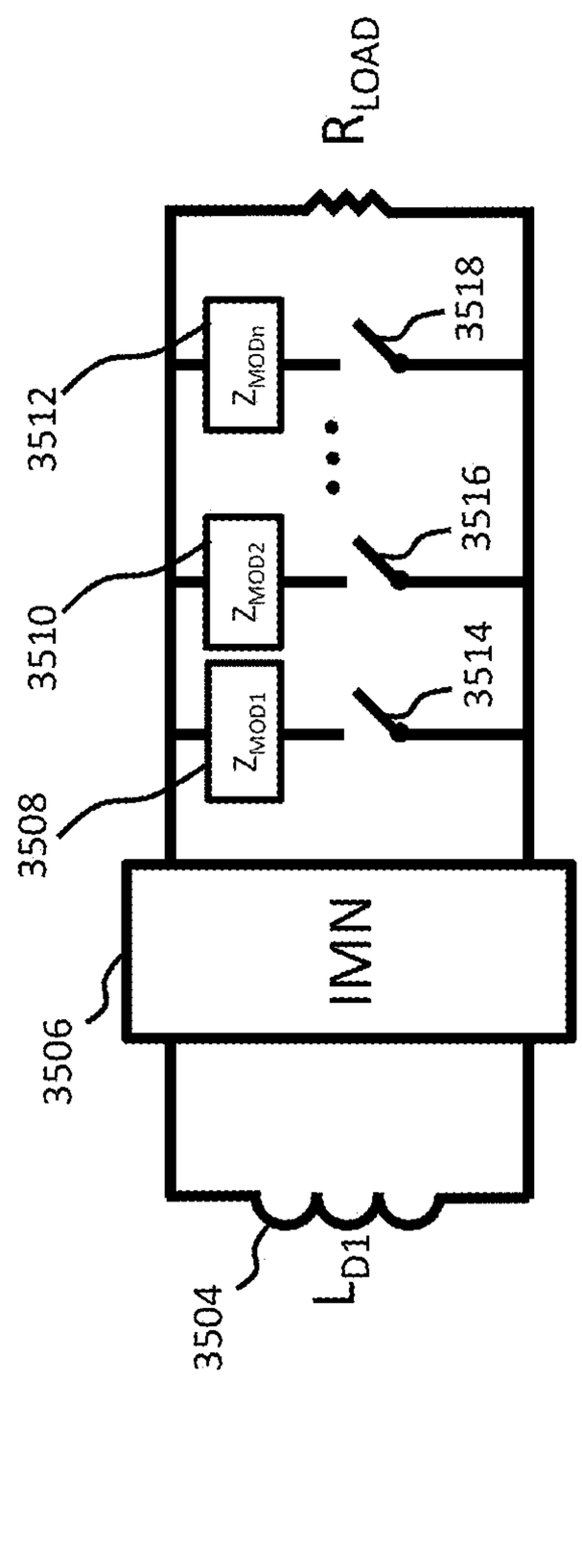
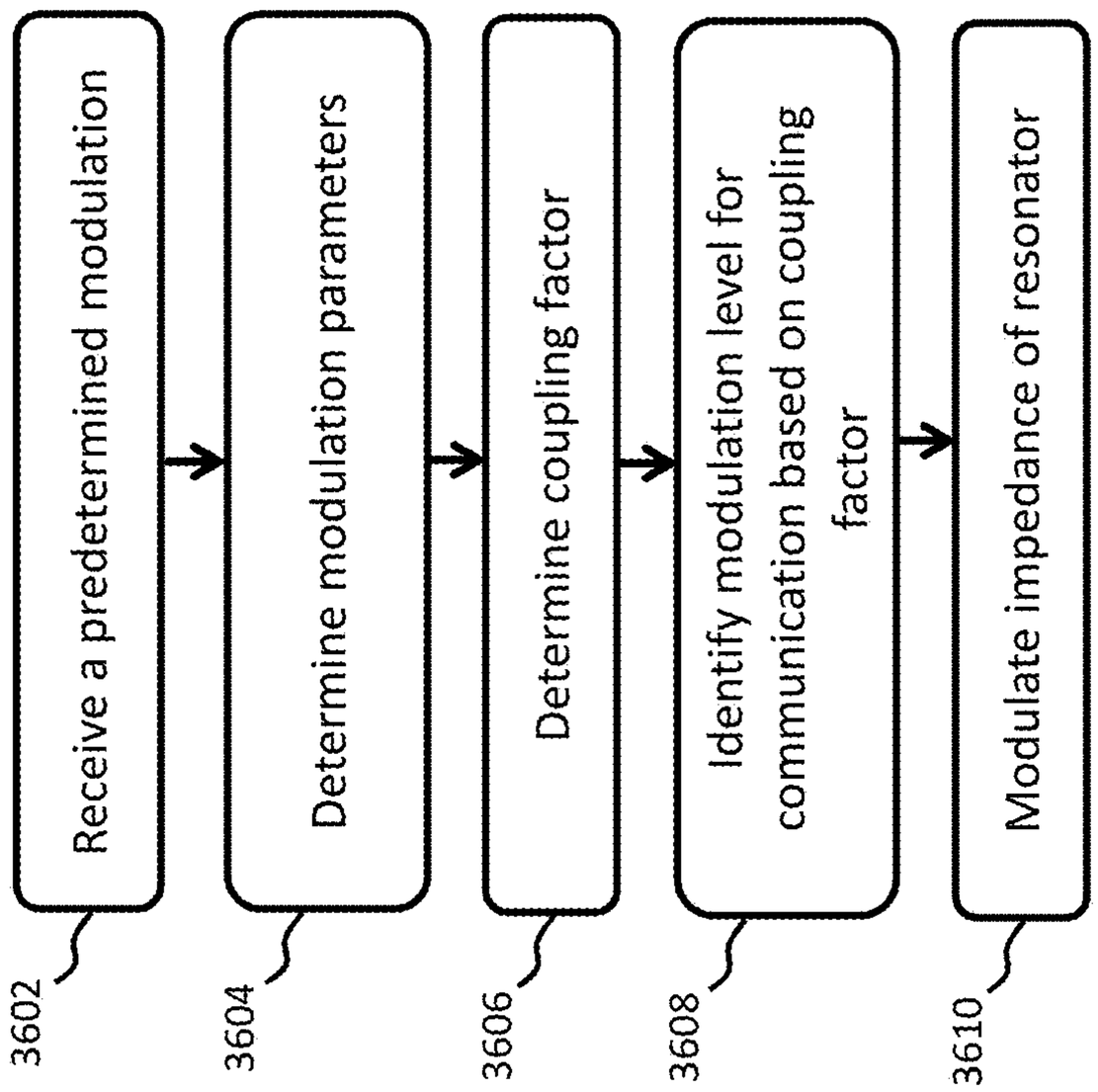

3502
3504
3506
IMN
3508
3510
3512
3514
3516
3518
Z_{MOD1}
Z_{MOD2}
Z_{MODn}
L_{D1}
R_{LOAD}

Fig. 36


Receive a predetermined modulation
Determine modulation parameters
Determine coupling factor
Identify modulation level for communication based on coupling factor
Modulate impedance of resonator
3602
3604
3606
3608
3610

COMMUNICATION IN WIRELESS ENERGY TRANSFER SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of the following applications each of which is hereby incorporated by reference in its entirety: U.S. Provisional Application 61/896,290, filed on Oct. 28, 2013; and U.S. Provisional Application No. 61/974,911 filed on Apr. 3, 2014.

[0002] This application is a continuation-in-part of U.S. Ser. No. 13/222,915 filed Aug. 31, 2011 and U.S. Ser. No. 13/288,589 filed Nov. 3, 2011.

[0003] The Ser. No. 13/222,915 application claims the benefit of U.S. Provisional Appl. No. 61/378,600 filed Aug. 31, 2010 and U.S. Provisional Appl. No. 61/411,490 filed Nov. 9, 2010.

[0004] The Ser. No. 13/288,589 application claims the benefit of U.S. Provisional Appl. No. 61/523,998 filed Aug. 16, 2011.

[0005] Each of the foregoing applications is incorporated herein by reference in its entirety and for all purposes.

BACKGROUND

[0006] Energy or power may be transferred wirelessly using a variety of known radiative, or far-field, and non-radiative, or near-field, techniques as detailed, for example, in commonly owned U.S. patent application Ser. No. 12/613,686 published on May 6, 2010 as US 2010/010909445 and entitled "Wireless Energy Transfer Systems," U.S. patent application Ser. No. 12/860,375 published on Dec. 9, 2010 as 2010/0308939 and entitled "Integrated Resonator-Shield Structures," U.S. patent application Ser. No. 13/222,915 published on Mar. 15, 2012 as 2012/0062345 and entitled "Low Resistance Electrical Conductor," the contents of which are incorporated by reference.

[0007] Wireless energy transfer may be difficult to incorporate or deploy in many environments. Efficiency of energy transfer, practicality, safety, cost, are factors that prohibit the deployment for many applications. Therefore, a need exists for a wireless energy transfer that addresses such practical challenges to allow widespread use of wireless energy transfer in typical user environments.

SUMMARY

[0008] Various systems and processes, in various embodiments, provide wireless energy transfer using coupled resonators.

[0009] In one aspect, the disclosure features methods that include transmitting, by a wireless power source, a signal with a first characteristic via an in-band communication channel, receiving via an out-of band communication channel, by the wireless power source, information from a first wireless power device, determining, by the wireless power source, if the information includes the first characteristic.

[0010] Embodiments of the methods can include any one or more of the following features. The methods can include transferring wireless power between the wireless power source and the first wireless power device if the information includes the first characteristic.

[0011] The methods can include receiving second information via the out-of-band communication channel if the information does not include the first characteristic; and determining, by the wireless power source, if the second information includes the first characteristic.

[0012] The signal can be a power transfer signal with a frequency approximately equal to a resonant frequency of the wireless power source.

[0013] The signal can be a modulated power transfer signal having a frequency and an amplitude.

[0014] The modulated power transfer signal can contain an identification code unique to the wireless power source.

[0015] The methods can include receiving via the out-of-band communication channel by the wireless power source, a second information from a second wireless power device, determining, by the wireless power source, if the second information includes the first characteristic, and transferring wireless power between the wireless power source and the second power device if the second information includes the signal.

[0016] The methods can include prioritizing wireless power transfer to the first and second wireless power devices.

[0017] The priority can be based on power demands of the first and second wireless power devices, order of pairing with one of the first and second power devices, type of device, or strength of coupling between the wireless power source and each of the first and second wireless power devices.

[0018] The methods can include transmitting a power control signal to one of the first and second wireless power devices that has a lower priority to detune itself.

[0019] In another aspect, the disclosure features methods that include receiving, by a wireless power device, a predetermined signal modulation from a wireless power source, determining, by the wireless power device, modulation parameters based on the predetermined signal modulation, determining, by the wireless power device, a coupling factor between the wireless power source and the wireless power device based the modulation parameters, modulating, by the wireless power device, the impedance of the wireless power device based on the coupling factor.

[0020] Embodiments of the methods can include any one or more of the following features. The methods can include monitoring the modulation of the impedance of the wireless power device at the wireless power source.

[0021] The methods can include changing, by the wireless power source, power output in response to the modulated impedance of the wireless power device.

[0022] The methods can include transmitting information from the wireless power device to the wireless power source using the modulated impedance.

[0023] The impedance can be the impedance of a device resonator of the wireless power device. The methods can include modulating the impedance of the wireless power device at one or more amplitudes and at one or more frequencies.

[0024] The impedance can be the impedance of the load of the wireless power device.

[0025] The methods can include monitoring for an impedance modulation of another wireless power device in the vicinity of the wireless power device.

[0026] This disclosure references certain individual circuit components and elements such as capacitors, inductors, resistors, diodes, transformers, switches and the like; combinations of these elements as networks, topologies, circuits, and the like; and objects that have inherent characteristics such as "self-resonant" objects with capacitance or inductance distributed (or partially distributed, as opposed to solely lumped)

throughout the entire object. It would be understood by one of ordinary skill in the art that adjusting and controlling variable components within a circuit or network may adjust the performance of that circuit or network and that those adjustments may be described generally as tuning, adjusting, matching, correcting, and the like. Other methods to tune or adjust the operating point of the wireless power transfer system may be used alone, or in addition to adjusting tunable components such as inductors and capacitors, or banks of inductors and capacitors. Those skilled in the art will recognize that a particular topology discussed in this disclosure can be implemented in a variety of other ways.

[0027] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. In case of conflict with publications, patent applications, patents, and other references mentioned or incorporated herein by reference, the present specification, including definitions, will control.

[0028] Any of the features described above may be used, alone or in combination, without departing from the scope of this disclosure. Other features, objects, and advantages of the systems and methods disclosed herein will be apparent from the following detailed description and figures.

BRIEF DESCRIPTION OF DRAWINGS

[0029] FIG. **1** is a system block diagram of wireless energy transfer configurations.

[0030] FIGS. **2**A-**2**F are exemplary structures and schematics of simple resonator structures.

[0031] FIG. **3** is a block diagram of a wireless source with a single-ended amplifier.

[0032] FIG. **4** is a block diagram of a wireless source with a differential amplifier.

[0033] FIGS. **5**A and **5**B are block diagrams of sensing circuits.

[0034] FIGS. **6**A, **6**B, and **6**C are block diagrams of a wireless source.

[0035] FIG. **7** is a plot showing the effects of a duty cycle on the parameters of an amplifier.

[0036] FIG. **8** is a simplified circuit diagram of a wireless power source with a switching amplifier.

[0037] FIG. **9** shows plots of the effects of changes of parameters of a wireless power source.

[0038] FIG. **10** shows plots of the effects of changes of parameters of a wireless power source.

[0039] FIGS. **11**A, **11**B, and **11**C are plots showing the effects of changes of parameters of a wireless power source.

[0040] FIG. **12** shows plots of the effects of changes of parameters of a wireless power source.

[0041] FIG. **13** is a simplified circuit diagram of a wireless energy transfer system comprising a wireless power source with a switching amplifier and a wireless power device.

[0042] FIG. **14** shows plots of the effects of changes of parameters of a wireless power source.

[0043] FIG. **15** is a diagram of a resonator showing possible nonuniform magnetic field distributions due to irregular spacing between tiles of magnetic material.

[0044] FIG. **16** is a resonator with an arrangement of tiles in a block of magnetic material that may reduce hotspots in the magnetic material block.

[0045] FIG. **17**A is a resonator with a block of magnetic material comprising smaller individual tiles and **17**B and **17**C is the resonator with additional strips of thermally conductive material used for thermal management.

[0046] FIG. **18** is block diagram of a wireless energy transfer system with in-band and out-of-band communication channels.

[0047] FIG. **19**A and FIG. **19**B are steps that may be used to verify the energy transfer channel using an out-of-band communication channel.

[0048] FIG. **20** is an isometric view of a conductor wire comprising multiple conductor shells.

[0049] FIG. **21** is an isometric view of a conductor wire comprising multiple conductor shells.

[0050] FIG. **22** is a plot showing the current distributions for a solid conductor wire.

[0051] FIG. **23** is a plot showing the current distributions for a conductor wire comprising 25 conductor shells.

[0052] FIG. **24** is a plot showing the current distributions for a conductor wire comprising 25 conductor shells.

[0053] FIG. **25** is a plot showing the ratio of the resistance of an optimized conducting-shell structure with overall diameter 1 mm to the AC resistance of a solid conductor of the same diameter.

[0054] FIG. **26** is a plot showing the ratio of the resistance of an optimized conducting-shell structure with overall diameter 1 mm to the DC resistance of the same conductor (21.6 mgΩ/m).

[0055] FIG. **27** is a plot showing the ratio of the resistance of an optimized conducting-shell structure with overall diameter 1 mm to the resistance with the same number of elements, but with shells of (optimized) uniform thickness around a copper core.

[0056] FIG. **28** is plot showing a sawtooth waveform.

[0057] FIGS. **29**A and **29**B are plots showing examples of alternative waveforms.

[0058] FIG. **30** is block diagram of an embodiment of a system element configured for pairing.

[0059] FIG. **31** is an embodiment of a method for pairing of system elements.

[0060] FIG. **32** is another embodiment of a method for pairing of system elements.

[0061] FIG. **33** shows a plot of an example of signaling by a wireless power source.

[0062] FIG. **34** shows an embodiment of a wireless energy transfer system configuration.

[0063] FIG. **35** shows an embodiment of simplified device configured for in-band communication.

[0064] FIG. **36** is an embodiment of a method for establishing an in-band communication channel.

DETAILED DESCRIPTION

[0065] As described above, this disclosure relates to wireless energy transfer using coupled electromagnetic resonators. However, such energy transfer is not restricted to electromagnetic resonators, and the wireless energy transfer systems described herein are more general and may be implemented using a wide variety of resonators and resonant objects.

[0066] As those skilled in the art will recognize, important considerations for resonator-based power transfer include resonator efficiency and resonator coupling. Extensive discussion of such issues, e.g., coupled mode theory (CMT), coupling coefficients and factors, quality factors (also referred to as Q-factors), and impedance matching is provided, for example, in U.S. patent application Ser. No.

12/789,611 published on Sep. 23, 2010 as US 20100237709 and entitled "RESONATOR ARRAYS FOR WIRELESS ENERGY TRANSFER," and U.S. patent application Ser. No. 12/722,050 published on Jul. 22, 2010 as US 20100181843 and entitled "WIRELESS ENERGY TRANSFER FOR REFRIGERATOR APPLICATION" and incorporated herein by reference in its entirety as if fully set forth herein.

[0067] A resonator may be defined as a resonant structure that can store energy in at least two different forms, and where the stored energy oscillates between the two forms. The resonant structure will have a specific oscillation mode with a resonant (modal) frequency, f, and a resonant (modal) field. The angular resonant frequency, ω, may be defined as $\omega=2\pi f$ the resonant period, T, may be defined as $T=1/f=2\pi/\omega$, and the resonant wavelength, λ, may be defined as $\lambda=c/f$, where c is the speed of the associated field waves (light, for electromagnetic resonators). In the absence of loss mechanisms, coupling mechanisms or external energy supplying or draining mechanisms, the total amount of energy stored by the resonator, W, would stay fixed, but the form of the energy would oscillate between the two forms supported by the resonator, wherein one form would be maximum when the other is minimum and vice versa.

[0068] For example, a resonator may be constructed such that the two forms of stored energy are magnetic energy and electric energy. Further, the resonator may be constructed such that the electric energy stored by the electric field is primarily confined within the structure while the magnetic energy stored by the magnetic field is primarily in the region surrounding the resonator. In other words, the total electric and magnetic energies would be equal, but their localization would be different. Using such structures, energy exchange between at least two structures may be mediated by the resonant magnetic near-field of the at least two resonators. These types of resonators may be referred to as magnetic resonators.

[0069] An important parameter of resonators used in wireless power transmission systems is the Quality Factor, or Q-factor, or Q, of the resonator, which characterizes the energy decay and is inversely proportional to energy losses of the resonator. It may be defined as $Q=\omega*W/P$, where P is the time-averaged power lost at steady state. That is, a resonator with a high-Q has relatively low intrinsic losses and can store energy for a relatively long time. Since the resonator loses energy at its intrinsic decay rate, 2Γ, its Q, also referred to as its intrinsic Q, is given by $Q=\omega/2\Gamma$. The quality factor also represents the number of oscillation periods, T, it takes for the energy in the resonator to decay by a factor of e^{-2} m. Note that the quality factor or intrinsic quality factor or Q of the resonator is that due only to intrinsic loss mechanisms. The Q of a resonator connected to, or coupled to a power generator, g, or load, l, may be called the "loaded quality factor" or the "loaded Q". The Q of a resonator in the presence of an extraneous object that is not intended to be part of the energy transfer system may be called the "perturbed quality factor" or the "perturbed Q".

[0070] Resonators, coupled through any portion of their near-fields may interact and exchange energy. The efficiency of this energy transfer can be significantly enhanced if the resonators operate at substantially the same resonant frequency. By way of example, but not limitation, imagine a source resonator with Qs and a device resonator with Q_d. High-Q wireless energy transfer systems may utilize resonators that are high-Q. The Q of each resonator may be high. The geometric mean of the resonator Q's, $\sqrt{Q_sQ_d}$ may also or instead be high.

[0071] The coupling factor, k, is a number between $0\leq|k|\leq1$, and it may be independent (or nearly independent) of the resonant frequencies of the source and device resonators, when those are placed at sub-wavelength distances. Rather the coupling factor k may be determined mostly by the relative geometry and the distance between the source and device resonators where the physical decay-law of the field mediating their coupling is taken into account. The coupling coefficient used in CMT, $\kappa=k\sqrt{\omega_s\omega_d}/2$, may be a strong function of the resonant frequencies, as well as other properties of the resonator structures. In applications for wireless energy transfer utilizing the near-fields of the resonators, it is desirable to have the size of the resonator be much smaller than the resonant wavelength, so that power lost by radiation is reduced. In some embodiments, high-Q resonators are sub-wavelength structures. In some electromagnetic embodiments, high-Q resonator structures are designed to have resonant frequencies higher than 100 kHz. In other embodiments, the resonant frequencies may be less than 1 GHz.

[0072] In exemplary embodiments, the power radiated into the far-field by these sub wavelength resonators may be further reduced by lowering the resonant frequency of the resonators and the operating frequency of the system. In other embodiments, the far field radiation may be reduced by arranging for the far fields of two or more resonators to interfere destructively in the far field.

[0073] In a wireless energy transfer system a resonator may be used as a wireless energy source, a wireless energy capture device, a repeater or a combination thereof. In embodiments a resonator may alternate between transferring energy, receiving energy or relaying energy. In a wireless energy transfer system one or more magnetic resonators may be coupled to an energy source and be energized to produce an oscillating magnetic near-field. Other resonators that are within the oscillating magnetic near-fields may capture these fields and convert the energy into electrical energy that may be used to power or charge a load thereby enabling wireless transfer of useful energy.

[0074] The so-called "useful" energy in a useful energy exchange is the energy or power that must be delivered to a device in order to power or charge it at an acceptable rate. The transfer efficiency that corresponds to a useful energy exchange may be system or application-dependent. For example, high power vehicle charging applications that transfer kilowatts of power may need to be at least 80% efficient in order to supply useful amounts of power resulting in a useful energy exchange sufficient to recharge a vehicle battery without significantly heating up various components of the transfer system. In some consumer electronics applications, a useful energy exchange may include any energy transfer efficiencies greater than 10%, or any other amount acceptable to keep rechargeable batteries "topped off" and running for long periods of time. In implanted medical device applications, a useful energy exchange may be any exchange that does not harm the patient but that extends the life of a battery or wakes up a sensor or monitor or stimulator. In such applications, 100 mW of power or less may be useful. In distributed sensing applications, power transfer of microwatts may be useful, and transfer efficiencies may be well below 1%.

[0075] A useful energy exchange for wireless energy transfer in a powering or recharging application may be efficient,

highly efficient, or efficient enough, as long as the wasted energy levels, heat dissipation, and associated field strengths are within tolerable limits and are balanced appropriately with related factors such as cost, weight, size, and the like.

[0076] The resonators may be referred to as source resonators, device resonators, first resonators, second resonators, repeater resonators, and the like. Implementations may include three (3) or more resonators. For example, a single source resonator may transfer energy to multiple device resonators or multiple devices. Energy may be transferred from a first device to a second, and then from the second device to the third, and so forth. Multiple sources may transfer energy to a single device or to multiple devices connected to a single device resonator or to multiple devices connected to multiple device resonators. Resonators may serve alternately or simultaneously as sources, devices, and/or they may be used to relay power from a source in one location to a device in another location. Intermediate electromagnetic resonators may be used to extend the distance range of wireless energy transfer systems and/or to generate areas of concentrated magnetic near-fields. Multiple resonators may be daisy-chained together, exchanging energy over extended distances and with a wide range of sources and devices. For example, a source resonator may transfer power to a device resonator via several repeater resonators. Energy from a source may be transferred to a first repeater resonator, the first repeater resonator may transfer the power to a second repeater resonator and the second to a third and so on until the final repeater resonator transfers its energy to a device resonator. In this respect the range or distance of wireless energy transfer may be extended and/or tailored by adding repeater resonators. High power levels may be split between multiple sources, transferred to multiple devices and recombined at a distant location.

[0077] The resonators may be designed using coupled mode theory models, circuit models, electromagnetic field models, and the like. The resonators may be designed to have tunable characteristic sizes. The resonators may be designed to handle different power levels. In exemplary embodiments, high power resonators may require larger conductors and higher current or voltage rated components than lower power resonators.

[0078] FIG. **1** shows a diagram of exemplary configurations and arrangements of a wireless energy transfer system. A wireless energy transfer system may include at least one source resonator (R1)**104** (optionally R6, **112**) coupled to an energy source **102** and optionally a sensor and control unit **108**. The energy source may be a source of any type of energy capable of being converted into electrical energy that may be used to drive the source resonator **104**. The energy source may be a battery, a solar panel, the electrical mains, a wind or water turbine, an electromagnetic resonator, a generator, and the like. The electrical energy used to drive the magnetic resonator is converted into oscillating magnetic fields by the resonator. The oscillating magnetic fields may be captured by other resonators which may be device resonators (R2) **106**, (R3) **116** that are optionally coupled to an energy drain **110**. The oscillating fields may be optionally coupled to repeater resonators (R4, R5) that are configured to extend or tailor the wireless energy transfer region. Device resonators may capture the magnetic fields in the vicinity of source resonator(s), repeater resonators and other device resonators and convert them into electrical energy that may be used by an energy drain. The energy drain **110** may be an electrical, electronic, mechanical or chemical device and the like configured to receive electrical energy. Repeater resonators may capture magnetic fields in the vicinity of source, device and repeater resonator(s) and may pass the energy on to other resonators.

[0079] A wireless energy transfer system may comprise a single source resonator **104** coupled to an energy source **102** and a single device resonator **106** coupled to an energy drain **110**. In embodiments a wireless energy transfer system may comprise multiple source resonators coupled to one or more energy sources and may comprise multiple device resonators coupled to one or more energy drains.

[0080] In embodiments the energy may be transferred directly between a source resonator **104** and a device resonator **106**. In other embodiments the energy may be transferred from one or more source resonators **104**, **112** to one or more device resonators **106**, **116** via any number of intermediate resonators which may be device resonators, source resonators, repeater resonators, and the like. Energy may be transferred via a network or arrangement of resonators **114** that may include subnetworks **118**, **120** arranged in any combination of topologies such as token ring, mesh, ad hoc, and the like.

[0081] In embodiments the wireless energy transfer system may comprise a centralized sensing and control system **108**. In embodiments parameters of the resonators, energy sources, energy drains, network topologies, operating parameters, etc. may be monitored and adjusted from a control processor to meet specific operating parameters of the system. A central control processor may adjust parameters of individual components of the system to optimize global energy transfer efficiency, to optimize the amount of power transferred, and the like. Other embodiments may be designed to have a substantially distributed sensing and control system. Sensing and control may be incorporated into each resonator or group of resonators, energy sources, energy drains, and the like and may be configured to adjust the parameters of the individual components in the group to maximize or minimize the power delivered, to maximize energy transfer efficiency in that group and the like.

[0082] In embodiments, components of the wireless energy transfer system may have wireless or wired data communication links to other components such as devices, sources, repeaters, power sources, resonators, and the like and may transmit or receive data that can be used to enable the distributed or centralized sensing and control. A wireless communication channel may be separate from the wireless energy transfer channel, or it may be the same. In one embodiment the resonators used for power exchange may also be used to exchange information. In some cases, information may be exchanged by modulating a component in a source or device circuit and sensing that change with port parameter or other monitoring equipment. Resonators may signal each other by tuning, changing, varying, dithering, and the like, the resonator parameters such as the impedance of the resonators which may affect the reflected impedance of other resonators in the system. The systems and methods described herein may enable the simultaneous transmission of power and communication signals between resonators in wireless power transmission systems, or it may enable the transmission of power and communication signals during different time periods or at different frequencies using the same magnetic fields that are used during the wireless energy transfer. In other embodiments wireless communication may be enabled with a sepa-

rate wireless communication channel such as WiFi, Bluetooth, Infrared, NFC, and the like.

[0083] In embodiments, a wireless energy transfer system may include multiple resonators and overall system performance may be improved by control of various elements in the system. For example, devices with lower power requirements may tune their resonant frequency away from the resonant frequency of a high-power source that supplies power to devices with higher power requirements. For another example, devices needing less power may adjust their rectifier circuits so that they draw less power from the source. In these ways, low and high power devices may safely operate or charge from a single high power source. In addition, multiple devices in a charging zone may find the power available to them regulated according to any of a variety of consumption control algorithms such as First-Come-First-Serve, Best Effort, Guaranteed Power, etc. The power consumption algorithms may be hierarchical in nature, giving priority to certain users or types of devices, or it may support any number of users by equally sharing the power that is available in the source. Power may be shared by any of the multiplexing techniques described in this disclosure.

[0084] In embodiments electromagnetic resonators may be realized or implemented using a combination of shapes, structures, and configurations. Electromagnetic resonators may include an inductive element, a distributed inductance, or a combination of inductances with a total inductance, L, and a capacitive element, a distributed capacitance, or a combination of capacitances, with a total capacitance, C. A minimal circuit model of an electromagnetic resonator comprising capacitance, inductance and resistance, is shown in FIG. **2**F. The resonator may include an inductive element **238** and a capacitive element **240**. Provided with initial energy, such as electric field energy stored in the capacitor **240**, the system will oscillate as the capacitor discharges transferring energy into magnetic field energy stored in the inductor **238** which in turn transfers energy back into electric field energy stored in the capacitor **240**. Intrinsic losses in these electromagnetic resonators include losses due to resistance in the inductive and capacitive elements and to radiation losses, and are represented by the resistor, R, **242** in FIG. **2**F.

[0085] FIG. **2**A shows a simplified drawing of an exemplary magnetic resonator structure. The magnetic resonator may include a loop of conductor acting as an inductive element **202** and a capacitive element **204** at the ends of the conductor loop. The inductor **202** and capacitor **204** of an electromagnetic resonator may be bulk circuit elements, or the inductance and capacitance may be distributed and may result from the way the conductors are formed, shaped, or positioned, in the structure.

[0086] For example, the inductor **202** may be realized by shaping a conductor to enclose a surface area, as shown in FIGS. **2**A. This type of resonator may be referred to as a capacitively-loaded loop inductor. Note that we may use the terms "loop" or "coil" to indicate generally a conducting structure (wire, tube, strip, etc.), enclosing a surface of any shape and dimension, with any number of turns. In FIG. **2**A, the enclosed surface area is circular, but the surface may be any of a wide variety of other shapes and sizes and may be designed to achieve certain system performance specifications. In embodiments the inductance may be realized using inductor elements, distributed inductance, networks, arrays, series and parallel combinations of inductors and inductances, and the like. The inductance may be fixed or variable and may be used to vary impedance matching as well as resonant frequency operating conditions.

[0087] There are a variety of ways to realize the capacitance required to achieve the desired resonant frequency for a resonator structure. Capacitor plates **204** may be formed and utilized as shown in FIG. **2**A, or the capacitance may be distributed and be realized between adjacent windings of a multi-loop conductor. The capacitance may be realized using capacitor elements, distributed capacitance, networks, arrays, series and parallel combinations of capacitances, and the like. The capacitance may be fixed or variable and may be used to vary impedance matching as well as resonant frequency operating conditions.

[0088] The inductive elements used in magnetic resonators may contain more than one loop and may spiral inward or outward or up or down or in some combination of directions. In general, the magnetic resonators may have a variety of shapes, sizes and number of turns and they may be composed of a variety of conducing materials. The conductor **210**, for example, may be a wire, a Litz wire, a ribbon, a pipe, a trace formed from conducting ink, paint, gels, and the like or from single or multiple traces printed on a circuit board. An exemplary embodiment of a trace pattern on a substrate **208** forming inductive loops is depicted in FIG. **2**B.

[0089] In embodiments the inductive elements may be formed using magnetic materials of any size, shape thickness, and the like, and of materials with a wide range of permeability and loss values. These magnetic materials may be solid blocks, they may enclose hollow volumes, they may be formed from many smaller pieces of magnetic material tiled and or stacked together, and they may be integrated with conducting sheets or enclosures made from highly conducting materials. Conductors may be wrapped around the magnetic materials to generate the magnetic field. These conductors may be wrapped around one or more than one axis of the structure. Multiple conductors may be wrapped around the magnetic materials and combined in parallel, or in series, or via a switch to form customized near-field patterns and/or to orient the dipole moment of the structure. Examples of resonators comprising magnetic material are depicted in FIGS. **2**C, **2**D, **2**E. In FIG. **2**D the resonator comprises loops of conductor **224** wrapped around a core of magnetic material **222** creating a structure that has a magnetic dipole moment **228** that is parallel to the axis of the loops of the conductor **224**. The resonator may comprise multiple loops of conductor **216**, **212** wrapped in orthogonal directions around the magnetic material **214** forming a resonator with a magnetic dipole moment **218**, **220** that may be oriented in more than one direction as depicted in FIG. **2**C, depending on how the conductors are driven.

[0090] An electromagnetic resonator may have a characteristic, natural, or resonant frequency determined by its physical properties. This resonant frequency is the frequency at which the energy stored by the resonator oscillates between that stored by the electric field, W_E, ($W_E=q^2/2C$, where q is the charge on the capacitor, C) and that stored by the magnetic field, W_B, ($W_B=Li^2/2$, where i is the current through the inductor, L) of the resonator. The frequency at which this energy is exchanged may be called the characteristic frequency, the natural frequency, or the resonant frequency of the resonator, and is given by ω,

$$\omega = 2\pi f = \sqrt{1/LC}\,.$$

[0091] The resonant frequency of the resonator may be changed by tuning the inductance, L, and/or the capacitance, C, of the resonator. In one embodiment, system parameters are dynamically adjustable or tunable to achieve as close as possible to optimal operating conditions. However, based on the discussion above, efficient enough energy exchange may be realized even if some system parameters are not variable or components are not capable of dynamic adjustment.

[0092] In embodiments, a resonator may comprise an inductive element coupled to more than one capacitor arranged in a network of capacitors and circuit elements. In embodiments, the coupled network of capacitors and circuit elements may be used to define more than one resonant frequency of the resonator. In embodiments a resonator may be resonant, or partially resonant, at more than one frequency.

[0093] In embodiments, a wireless power source may comprise of at least one resonator coil coupled to a power supply, which may be a switching amplifier, such as a class-D amplifier or a class-E amplifier or a combination thereof. In this case, the resonator coil is effectively a power load to the power supply. In embodiments, a wireless power device may comprise of at least one resonator coil coupled to a power load, which may be a switching rectifier, such as a class-D rectifier or a class-E rectifier or a combination thereof. In this case, the resonator coil is effectively a power supply for the power load, and the impedance of the load directly relates also to the work-drainage rate of the load from the resonator coil. The efficiency of power transmission between a power supply and a power load may be impacted by how closely matched the output impedance of the power source is to the input impedance of the load. Power may be delivered to the load at a maximum possible efficiency, when the input impedance of the load is equal to the complex conjugate of the internal impedance of the power supply. Designing the power supply or power load impedance to obtain a maximum power transmission efficiency is often called "impedance matching", and may also referred to as optimizing the ratio of useful-to-lost powers in the system. Impedance matching may be performed by adding networks or sets of elements such as capacitors, inductors, transformers, switches, resistors, and the like, to form impedance matching networks between a power supply and a power load. In embodiments, mechanical adjustments and changes in element positioning may be used to achieve impedance matching. For varying loads, the impedance matching network may include variable components that are dynamically adjusted to ensure that the impedance at the power supply terminals looking towards the load and the characteristic impedance of the power supply remain substantially complex conjugates of each other, even in dynamic environments and operating scenarios.

[0094] In embodiments, impedance matching may be accomplished by tuning the duty cycle, and/or the phase, and/or the frequency of the driving signal of the power supply or by tuning a physical component within the power supply, such as a capacitor. Such a tuning mechanism may be advantageous because it may allow impedance matching between a power supply and a load without the use of a tunable impedance matching network, or with a simplified tunable impedance matching network, such as one that has fewer tunable components for example. In embodiments, tuning the duty cycle, and/or frequency, and/or phase of the driving signal to a power supply may yield a dynamic impedance matching system with an extended tuning range or precision, with higher power, voltage and/or current capabilities, with faster electronic control, with fewer external components, and the like.

[0095] In some wireless energy transfer systems the parameters of the resonator such as the inductance may be affected by environmental conditions such as surrounding objects, temperature, orientation, number and position of other resonators and the like. Changes in operating parameters of the resonators may change certain system parameters, such as the efficiency of transferred power in the wireless energy transfer. For example, high-conductivity materials located near a resonator may shift the resonant frequency of a resonator and detune it from other resonant objects. In some embodiments, a resonator feedback mechanism is employed that corrects its frequency by changing a reactive element (e.g., an inductive element or capacitive element). In order to achieve acceptable matching conditions, at least some of the system parameters may need to be dynamically adjustable or tunable. All the system parameters may be dynamically adjustable or tunable to achieve approximately the optimal operating conditions. However, efficient enough energy exchange may be realized even if all or some system parameters are not variable. In some examples, at least some of the devices may not be dynamically adjusted. In some examples, at least some of the sources may not be dynamically adjusted. In some examples, at least some of the intermediate resonators may not be dynamically adjusted. In some examples, none of the system parameters may be dynamically adjusted.

[0096] In some embodiments changes in parameters of components may be mitigated by selecting components with characteristics that change in a complimentary or opposite way or direction when subjected to differences in operating environment or operating point. In embodiments, a system may be designed with components, such as capacitors, that have an opposite dependence or parameter fluctuation due to temperature, power levels, frequency, and the like. In some embodiments, the component values as a function of temperature may be stored in a look-up table in a system microcontroller and the reading from a temperature sensor may be used in the system control feedback loop to adjust other parameters to compensate for the temperature induced component value changes.

[0097] In some embodiments the changes in parameter values of components may be compensated with active tuning circuits comprising tunable components. Circuits that monitor the operating environment and operating point of components and system may be integrated in the design. The monitoring circuits may provide the signals necessary to actively compensate for changes in parameters of components. For example, a temperature reading may be used to calculate expected changes in, or to indicate previously measured values of, capacitance of the system allowing compensation by switching in other capacitors or tuning capacitors to maintain the desired capacitance over a range of temperatures. In embodiments, the RF amplifier switching waveforms may be adjusted to compensate for component value or load changes in the system. In some embodiments the changes in parameters of components may be compensated with active cooling, heating, active environment conditioning, and the like.

[0098] The parameter measurement circuitry may measure or monitor certain power, voltage, and current, signals in the

system, and processors or control circuits may adjust certain settings or operating parameters based on those measurements. In addition the magnitude and phase of voltage and current signals, and the magnitude of the power signals, throughout the system may be accessed to measure or monitor the system performance. The measured signals referred to throughout this disclosure may be any combination of port parameter signals, as well as voltage signals, current signals, power signals, temperatures signals and the like. These parameters may be measured using analog or digital techniques, they may be sampled and processed, and they may be digitized or converted using a number of known analog and digital processing techniques. In embodiments, preset values of certain measured quantities are loaded in a system controller or memory location and used in various feedback and control loops. In embodiments, any combination of measured, monitored, and/or preset signals may be used in feedback circuits or systems to control the operation of the resonators and/or the system.

[0099] Adjustment algorithms may be used to adjust the frequency, Q, and/or impedance of the magnetic resonators. The algorithms may take as inputs reference signals related to the degree of deviation from a desired operating point for the system and may output correction or control signals related to that deviation that control variable or tunable elements of the system to bring the system back towards the desired operating point or points. The reference signals for the magnetic resonators may be acquired while the resonators are exchanging power in a wireless power transmission system, or they may be switched out of the circuit during system operation. Corrections to the system may be applied or performed continuously, periodically, upon a threshold crossing, digitally, using analog methods, and the like.

[0100] In embodiments, lossy extraneous materials and objects may introduce potential reductions in efficiencies by absorbing the magnetic and/or electric energy of the resonators of the wireless power transmission system. Those impacts may be mitigated in various embodiments by positioning resonators to minimize the effects of the lossy extraneous materials and objects and by placing structural field shaping elements (e.g., conductive structures, plates and sheets, magnetic material structures, plates and sheets, and combinations thereof) to minimize their effect.

[0101] One way to reduce the impact of lossy materials on a resonator is to use high-conductivity materials, magnetic materials, or combinations thereof to shape the resonator fields such that they avoid the lossy objects. In an exemplary embodiment, a layered structure of high-conductivity material and magnetic material may tailor, shape, direct, reorient, etc. the resonator's electromagnetic fields so that they avoid lossy objects in their vicinity by deflecting the fields. FIG. **2**D shows a top view of a resonator with a sheet of conductor **226** below the magnetic material that may be used to tailor the fields of the resonator so that they avoid lossy objects that may be below the sheet of conductor **226**. The layer or sheet of good **226** conductor may comprise any high conductivity materials such as copper, silver, aluminum, as may be most appropriate for a given application. In certain embodiments, the layer or sheet of good conductor is thicker than the skin depth of the conductor at the resonator operating frequency. The conductor sheet may be preferably larger than the size of the resonator, extending beyond the physical extent of the resonator.

[0102] In environments and systems where the amount of power being transmitted could present a safety hazard to a person or animal that may intrude into the active field volume, safety measures may be included in the system. In embodiments where power levels require particularized safety measures, the packaging, structure, materials, and the like of the resonators may be designed to provide a spacing or "keep away" zone from the conducting loops in the magnetic resonator. To provide further protection, high-Q resonators and power and control circuitry may be located in enclosures that confine high voltages or currents to within the enclosure, that protect the resonators and electrical components from weather, moisture, sand, dust, and other external elements, as well as from impacts, vibrations, scrapes, explosions, and other types of mechanical shock. Such enclosures call for attention to various factors such as thermal dissipation to maintain an acceptable operating temperature range for the electrical components and the resonator. In embodiments, enclosure may be constructed of non-lossy materials such as composites, plastics, wood, concrete, and the like and may be used to provide a minimum distance from lossy objects to the resonator components. A minimum separation distance from lossy objects or environments which may include metal objects, salt water, oil and the like, may improve the efficiency of wireless energy transfer. In embodiments, a "keep away" zone may be used to increase the perturbed Q of a resonator or system of resonators. In embodiments a minimum separation distance may provide for a more reliable or more constant operating parameters of the resonators.

[0103] In embodiments, resonators and their respective sensor and control circuitry may have various levels of integration with other electronic and control systems and subsystems. In some embodiments the power and control circuitry and the device resonators are completely separate modules or enclosures with minimal integration to existing systems, providing a power output and a control and diagnostics interface. In some embodiments a device is configured to house a resonator and circuit assembly in a cavity inside the enclosure, or integrated into the housing or enclosure of the device.

[0104] Example Resonator Circuitry

[0105] FIGS. **3** and **4** show high level block diagrams depicting power generation, monitoring, and control components for exemplary sources of a wireless energy transfer system. FIG. **3** is a block diagram of a source comprising a half-bridge switching power amplifier and some of the associated measurement, tuning, and control circuitry. FIG. **4** is a block diagram of a source comprising a full-bridge switching amplifier and some of the associated measurement, tuning, and control circuitry.

[0106] The half bridge system topology depicted in FIG. **3** may comprise a processing unit that executes a control algorithm **328**. The processing unit executing a control algorithm **328** may be a microcontroller, an application specific circuit, a field programmable gate array, a processor, a digital signal processor, and the like. The processing unit may be a single device or it may be a network of devices. The control algorithm may run on any portion of the processing unit. The algorithm may be customized for certain applications and may comprise a combination of analog and digital circuits and signals. The master algorithm may measure and adjust voltage signals and levels, current signals and levels, signal phases, digital count settings, and the like.

[0107] The system may comprise an optional source/device and/or source/other resonator communication controller **332** coupled to wireless communication circuitry **312**. The optional source/device and/or source/other resonator communication controller **332** may be part of the same processing unit that executes the master control algorithm, it may a part or a circuit within a microcontroller **302**, it may be external to the wireless power transmission modules, it may be substantially similar to communication controllers used in wire powered or battery powered applications but adapted to include some new or different functionality to enhance or support wireless power transmission.

[0108] The system may comprise a PWM generator **306** coupled to at least two transistor gate drivers **334** and may be controlled by the control algorithm. The two transistor gate drivers **334** may be coupled directly or via gate drive transformers to two power transistors **336** that drive the source resonator coil **344** through impedance matching network components **342**. The power transistors **336** may be coupled and powered with an adjustable DC supply **304** and the adjustable DC supply **304** may be controlled by a variable bus voltage, Vbus. The Vbus controller may be controlled by the control algorithm **328** and may be part of, or integrated into, a microcontroller **302** or other integrated circuits. The Vbus controller **326** may control the voltage output of an adjustable DC supply **304** which may be used to control power output of the amplifier and power delivered to the resonator coil **344**.

[0109] The system may comprise sensing and measurement circuitry including signal filtering and buffering circuits **318**, **320** that may shape, modify, filter, process, buffer, and the like, signals prior to their input to processors and/or converters such as analog to digital converters (ADC) **314**, **316**, for example. The processors and converters such as ADCs **314**, **316** may be integrated into a microcontroller **302** or may be separate circuits that may be coupled to a processing core **330**. Based on measured signals, the control algorithm **328** may generate, limit, initiate, extinguish, control, adjust, or modify the operation of any of the PWM generator **306**, the communication controller **332**, the Vbus control **326**, the source impedance matching controller **338**, the filter/buffering elements, **318**, **320**, the converters, **314**, **316**, the resonator coil **344**, and may be part of, or integrated into, a microcontroller **302** or a separate circuit. The impedance matching networks **342** and resonator coils **344** may include electrically controllable, variable, or tunable components such as capacitors, switches, inductors, and the like, as described herein, and these components may have their component values or operating points adjusted according to signals received from the source impedance matching controller **338**. Components may be tuned to adjust the operation and characteristics of the resonator including the power delivered to and by the resonator, the resonant frequency of the resonator, the impedance of the resonator, the Q of the resonator, and any other coupled systems, and the like. The resonator may be any type or structure resonator described herein including a capacitively loaded loop resonator, a planer resonator comprising a magnetic material or any combination thereof.

[0110] The full bridge system topology depicted in FIG. **4** may comprise a processing unit that executes a master control algorithm **328**. The processing unit executing the control algorithm **328** may be a microcontroller, an application specific circuit, a field programmable gate array, a processor, a digital signal processor, and the like. The system may comprise a source/device and/or source/other resonator communication controller **332** coupled to wireless communication circuitry **312**. The source/device and/or source/other resonator communication controller **332** may be part of the same processing unit that executes that master control algorithm, it may a part or a circuit within a microcontroller **302**, it may be external to the wireless power transmission modules, it may be substantially similar to communication controllers used in wire powered or battery powered applications but adapted to include some new or different functionality to enhance or support wireless power transmission.

[0111] The system may comprise a PWM generator **410** with at least two outputs coupled to at least four transistor gate drivers **334** that may be controlled by signals generated in a master control algorithm. The four transistor gate drivers **334** may be coupled to four power transistors **336** directly or via gate drive transformers that may drive the source resonator coil **344** through impedance matching networks **342**. The power transistors **336** may be coupled and powered with an adjustable DC supply **304** and the adjustable DC supply **304** may be controlled by a Vbus controller **326** which may be controlled by a master control algorithm. The Vbus controller **326** may control the voltage output of the adjustable DC supply **304** which may be used to control power output of the amplifier and power delivered to the resonator coil **344**.

[0112] The system may comprise sensing and measurement circuitry including signal filtering and buffering circuits **318**, **320** and differential/single ended conversion circuitry **402**, **404** that may shape, modify, filter, process, buffer, and the like, signals prior to being input to processors and/or converters such as analog to digital converters (ADC) **314**, **316**. The processors and/or converters such as ADC **314**, **316** may be integrated into a microcontroller **302** or may be separate circuits that may be coupled to a processing core **330**. Based on measured signals, the master control algorithm may generate, limit, initiate, extinguish, control, adjust, or modify the operation of any of the PWM generator **410**, the communication controller **332**, the Vbus controller **326**, the source impedance matching controller **338**, the filter/buffering elements, **318**, **320**, differential/single ended conversion circuitry **402**, **404**, the converters, **314**, **316**, the resonator coil **344**, and may be part of or integrated into a microcontroller **302** or a separate circuit.

[0113] Impedance matching networks **342** and resonator coils **344** may comprise electrically controllable, variable, or tunable components such as capacitors, switches, inductors, and the like, as described herein, and these components may have their component values or operating points adjusted according to signals received from the source impedance matching controller **338**. Components may be tuned to enable tuning of the operation and characteristics of the resonator including the power delivered to and by the resonator, the resonant frequency of the resonator, the impedance of the resonator, the Q of the resonator, and any other coupled systems, and the like. The resonator may be any type or structure resonator described herein including a capacitively loaded loop resonator, a planar resonator comprising a magnetic material or any combination thereof.

[0114] Impedance matching networks may comprise fixed value components such as capacitors, inductors, and networks of components as described herein. Parts of the impedance matching networks, A, B and C, may comprise inductors, capacitors, transformers, and series and parallel combinations of such components, as described herein. In some embodiments, parts of the impedance matching net-

works A, B, and C, may be empty (short-circuited). In some embodiments, part B comprises a series combination of an inductor and a capacitor, and part C is empty.

[0115] The full bridge topology may allow operation at higher output power levels using the same DC bus voltage as an equivalent half bridge amplifier. The half bridge exemplary topology of FIG. **3** may provide a single-ended drive signal, while the exemplary full bridge topology of FIG. **4** may provide a differential drive to the source resonator **308**. The impedance matching topologies and components and the resonator structure may be different for the two systems, as discussed herein.

[0116] The exemplary systems depicted in FIGS. **3** and **4** may further include fault detection circuitry **340** that may be used to trigger the shutdown of the microcontroller in the source amplifier or to change or interrupt the operation of the amplifier. This protection circuitry may comprise a high speed comparator or comparators to monitor the amplifier return current, the amplifier bus voltage (Vbus) from the DC supply **304**, the voltage across the source resonator **308** and/or the optional tuning board, or any other voltage or current signals that may cause damage to components in the system or may yield undesirable operating conditions. Preferred embodiments may depend on the potentially undesirable operating modes associated with different applications. In some embodiments, protection circuitry may not be implemented or circuits may not be populated. In some embodiments, system and component protection may be implemented as part of a master control algorithm and other system monitoring and control circuits. In embodiments, dedicated fault circuitry **340** may include an output (not shown) coupled to a master control algorithm **328** that may trigger a system shutdown, a reduction of the output power (e.g. reduction of Vbus), a change to the PWM generator, a change in the operating frequency, a change to a tuning element, or any other reasonable action that may be implemented by the control algorithm **328** to adjust the operating point mode, improve system performance, and/or provide protection.

[0117] As described herein, sources in wireless power transfer systems may use a measurement of the input impedance of the impedance matching network **342** driving source resonator coil **344** as an error or control signal for a system control loop that may be part of the master control algorithm. In exemplary embodiments, variations in any combination of three parameters may be used to tune the wireless power source to compensate for changes in environmental conditions, for changes in coupling, for changes in device power demand, for changes in module, circuit, component or subsystem performance, for an increase or decrease in the number or sources, devices, or repeaters in the system, for user initiated changes, and the like. In exemplary embodiments, changes to the amplifier duty cycle, to the component values of the variable electrical components such as variable capacitors and inductors, and to the DC bus voltage may be used to change the operating point or operating range of the wireless source and improve some system operating value. The specifics of the control algorithms employed for different applications may vary depending on the desired system performance and behavior.

[0118] Impedance measurement circuitry such as described herein, and shown in FIGS. **3** and **4**, may be implemented using two-channel simultaneous sampling ADCs and these ADCs may be integrated into a microcontroller chip or may be part of a separate circuit. Simultaneously sampling of the voltage and current signals at the input to a source resonator's impedance matching network and/or the source resonator, may yield the phase and magnitude information of the current and voltage signals and may be processed using known signal processing techniques to yield complex impedance parameters. In some embodiments, monitoring only the voltage signals or only the current signals may be sufficient.

[0119] The impedance measurements described herein may use direct sampling methods which may be relatively simpler than some other known sampling methods. In embodiments, measured voltage and current signals may be conditioned, filtered and scaled by filtering/buffering circuitry before being input to ADCs. In embodiments, the filter/buffering circuitry may be adjustable to work at a variety of signal levels and frequencies, and circuit parameters such as filter shapes and widths may be adjusted manually, electronically, automatically, in response to a control signal, by the master control algorithm, and the like. Exemplary embodiments of filter/buffering circuits are shown in FIGS. **3**, **4**, and **5**.

[0120] FIG. **5** shows more detailed views of exemplary circuit components that may be used in filter/buffering circuitry. In embodiments, and depending on the types of ADCs used in the system designs, single-ended amplifier topologies may reduce the complexity of the analog signal measurement paths used to characterize system, subsystem, module and/or component performance by eliminating the need for hardware to convert from differential to single-ended signal formats. In other implementations, differential signal formats may be preferable. The implementations shown in FIG. **5** are exemplary, and should not be construed to be the only possible way to implement the functionality described herein. Rather it should be understood that the analog signal path may employ components with different input requirements and hence may have different signal path architectures.

[0121] In both the single ended and differential amplifier topologies, the input current to the impedance matching networks **342** driving the resonator coils **344** may be obtained by measuring the voltage across a capacitor **324**, or via a current sensor of some type. For the exemplary single-ended amplifier topology in FIG. **3**, the current may be sensed on the ground return path from the impedance matching network **342**. For the exemplary differential power amplifier depicted in FIG. **4**, the input current to the impedance matching networks **342** driving the resonator coils **344** may be measured using a differential amplifier across the terminals of a capacitor **324** or via a current sensor of some type. In the differential topology of FIG. **4**, the capacitor **324** may be duplicated at the negative output terminal of the source power amplifier.

[0122] In both topologies, after single ended signals representing the input voltage and current to the source resonator and impedance matching network are obtained, the signals may be filtered **502** to obtain the desired portions of the signal waveforms. In embodiments, the signals may be filtered to obtain the fundamental component of the signals. In embodiments, the type of filtering performed, such as low pass, bandpass, notch, and the like, as well as the filter topology used, such as elliptical, Chebyshev, Butterworth, and the like, may depend on the specific requirements of the system. In some embodiments, no filtering will be required.

[0123] The voltage and current signals may be amplified by an optional amplifier **504**. The gain of the optional amplifier **504** may be fixed or variable. The gain of the amplifier may be controlled manually, electronically, automatically, in

response to a control signal, and the like. The gain of the amplifier may be adjusted in a feedback loop, in response to a control algorithm, by the master control algorithm, and the like. In embodiments, required performance specifications for the amplifier may depend on signal strength and desired measurement accuracy, and may be different for different application scenarios and control algorithms.

[0124] The measured analog signals may have a DC offset added to them, **506**, which may be required to bring the signals into the input voltage range of the ADC which for some systems may be 0 to 3.3V. In some systems this stage may not be required, depending on the specifications of the particular ADC used.

[0125] As described above, the efficiency of power transmission between a power generator and a power load may be impacted by how closely matched the output impedance of the generator is to the input impedance of the load. In an exemplary system as shown in FIG. **6**A, power may be delivered to the load at a maximum possible efficiency, when the input impedance of the load **604** is equal to the complex conjugate of the internal impedance of the power generator or the power amplifier **602**. Designing the generator or load impedance to obtain a high and/or maximum power transmission efficiency may be called "impedance matching". Impedance matching may be performed by inserting appropriate networks or sets of elements such as capacitors, resistors, inductors, transformers, switches and the like, to form an impedance matching network **606**, between a power generator **602** and a power load **604** as shown in FIG. **6**B. In other embodiments, mechanical adjustments and changes in element positioning may be used to achieve impedance matching. As described above for varying loads, the impedance matching network **606** may include variable components that are dynamically adjusted to ensure that the impedance at the generator terminals looking towards the load and the characteristic impedance of the generator remain substantially complex conjugates of each other, even in dynamic environments and operating scenarios. In embodiments, dynamic impedance matching may be accomplished by tuning the duty cycle, and/or the phase, and/or the frequency of the driving signal of the power generator or by tuning a physical component within the power generator, such as a capacitor, as depicted in FIG. **6**C. Such a tuning mechanism may be advantageous because it may allow impedance matching between a power generator **608** and a load without the use of a tunable impedance matching network, or with a simplified tunable impedance matching network **606**, such as one that has fewer tunable components for example. In embodiments, tuning the duty cycle, and/or frequency, and/or phase of the driving signal to a power generator may yield a dynamic impedance matching system with an extended tuning range or precision, with higher power, voltage and/or current capabilities, with faster electronic control, with fewer external components, and the like. The impedance matching methods, architectures, algorithms, protocols, circuits, measurements, controls, and the like, described below, may be useful in systems where power generators drive high-Q magnetic resonators and in high-Q wireless power transmission systems as described herein. In wireless power transfer systems a power generator may be a power amplifier driving a resonator, sometimes referred to as a source resonator, which may be a load to the power amplifier. In wireless power applications, it may be preferable to control the impedance matching between a power amplifier and a resonator load to control the efficiency of the power delivery from the power amplifier to the resonator. The impedance matching may be accomplished, or accomplished in part, by tuning or adjusting the duty cycle, and/or the phase, and/or the frequency of the driving signal of the power amplifier that drives the resonator.

[0126] Efficiency of Switching Amplifiers

[0127] Switching amplifiers, such as class D, E, F amplifiers, and the like or any combinations thereof, deliver power to a load at a maximum efficiency when almost no power is dissipated on the switching elements of the amplifier. This operating condition may be accomplished by designing the system so that the switching operations which are most critical (namely those that are most likely to lead to switching losses) are done when either or both of the voltage across the switching element and the current through the switching element are nearly zero. These conditions may be referred to as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) conditions respectively. When an amplifier operates at ZVS and/or ZCS either the voltage across the switching element or the current through the switching element is zero and thus no power can be dissipated in the switch. Since a switching amplifier may convert DC (or very low frequency AC) power to AC power at a specific frequency or range of frequencies, a filter may be introduced before the load to prevent unwanted harmonics that may be generated by the switching process from reaching the load and being dissipated there. In embodiments, a switching amplifier may be designed to operate at maximum efficiency of power conversion, when connected to a resonant load, with a quality factor (say Q>5), and of a specific impedance $Z^*_o=R_o+jX_o$, which leads to simultaneous ZVS and ZCS. We define $Z_o=R_o-jX_o$ as the characteristic impedance of the amplifier, so that achieving maximum power transmission efficiency is equivalent to impedance matching the resonant load to the characteristic impedance of the amplifier.

[0128] In a switching amplifier, the switching frequency of the switching elements, f_{switch}, wherein $f_{switch}=\omega/2\pi$ and the duty cycle, dc, of the ON switch-state duration of the switching elements may be the same for all switching elements of the amplifier. In this specification, we will use the term "class D" to denote both class D and class DE amplifiers, that is, switching amplifiers with dc<=50%.

[0129] The value of the characteristic impedance of the amplifier may depend on the operating frequency, the amplifier topology, and the switching sequence of the switching elements. In some embodiments, the switching amplifier may be a half-bridge topology and, in some embodiments, a full-bridge topology. In some embodiments, the switching amplifier may be class D and, in some embodiments, class E. In any of the above embodiments, assuming the elements of the bridge are symmetric, the characteristic impedance of the switching amplifier has the form

$$R_o=F_R(\mathrm{dc})/\omega C_a, X_o=F_X(\mathrm{dc})/\omega C_a \quad (1)$$

[0130] where dc is the duty cycle of ON switch-state of the switching elements, the functions $F_R(\mathrm{dc})$ and $F_X(\mathrm{dc})$ are plotted in FIG. **7** (both for class D and E), ω is the frequency at which the switching elements are switched, and $C_a=n_aC_{switc}$ where C_{switc} is the capacitance across each switch, including both the transistor output capacitance and also possible external capacitors placed in parallel with the switch, while $n_a=1$ for a full bridge and $n_a=2$ for a half bridge. For class D, one can also write the analytical expressions

$$F_R(\mathrm{dc})=\sin^2 u/\pi, F_R(\mathrm{dc})=(u-\sin u*\cos u)\pi, \quad (2)$$

[0131] where u=π(1−2*dc), indicating that the characteristic impedance level of a class D amplifier decreases as the duty cycle, dc, increases towards 50%. For a class D amplifier operation with dc=50%, achieving ZVS and ZCS is possible only when the switching elements have practically no output capacitance (C_a=0) and the load is exactly on resonance (X_o=0), while R_o can be arbitrary.

[0132] Impedance Matching Networks. In applications, the driven load may have impedance that is very different from the characteristic impedance of the external driving circuit, to which it is connected. Furthermore, the driven load may not be a resonant network. An Impedance Matching Network (IMN) is a circuit network that may be connected before a load as in FIG. **6**B, in order to regulate the impedance that is seen at the input of the network consisting of the IMN circuit and the load. An IMN circuit may typically achieve this regulation by creating a resonance close to the driving frequency. Since such an IMN circuit accomplishes all conditions needed to maximize the power transmission efficiency from the generator to the load (resonance and impedance matching—ZVS and ZCS for a switching amplifier), in embodiments, an IMN circuit may be used between the driving circuit and the load.

[0133] For an arrangement shown in FIG. **6**B, let the input impedance of the network consisting of the Impedance Matching Network (IMN) circuit and the load (denoted together from now on as IMN+load) be $Z_I=R_I(\omega)+jX_I(\omega)$. The impedance matching conditions of this network to the external circuit with characteristic impedance $Z_o=R_o-jX_o$ are then $R_I(\omega)=R_o$, $X_I(\omega)=X_o$.

[0134] Methods for Tunable Impedance Matching of a Variable Load

[0135] In embodiments where the load may be variable, impedance matching between the load and the external driving circuit, such as a linear or switching power amplifier, may be achieved by using adjustable/tunable components in the IMN circuit that may be adjusted to match the varying load to the fixed characteristic impedance Z_o of the external circuit (FIG. **6**B). To match both the real and imaginary parts of the impedance two tunable/variable elements in the IMN circuit may be needed.

[0136] In embodiments, the load may be inductive (such as a resonator coil) with impedance R+jωL, so the two tunable elements in the IMN circuit may be two tunable capacitance networks or one tunable capacitance network and one tunable inductance network or one tunable capacitance network and one tunable mutual inductance network.

[0137] In embodiments where the load may be variable, the impedance matching between the load and the driving circuit, such as a linear or switching power amplifier, may be achieved by using adjustable/tunable components or parameters in the amplifier circuit that may be adjusted to match the characteristic impedance Z_o of the amplifier to the varying (due to load variations) input impedance of the network consisting of the IMN circuit and the load (IMN+load), where the IMN circuit may also be tunable (FIG. **6**C). To match both the real and imaginary parts of the impedance, a total of two tunable/variable elements or parameters in the amplifier and the IMN circuit may be needed. The disclosed impedance matching method can reduce the required number of tunable/variable elements in the IMN circuit or even completely eliminate the requirement for tunable/variable elements in the IMN circuit. In some examples, one tunable element in the power amplifier and one tunable element in the IMN circuit may be used. In some examples, two tunable elements in the power amplifier and no tunable element in the IMN circuit may be used.

[0138] In embodiments, the tunable elements or parameters in the power amplifier may be the frequency, amplitude, phase, waveform, duty cycle and the like of the drive signals applied to transistors, switches, diodes and the like.

[0139] In embodiments, the power amplifier with tunable characteristic impedance may be a tunable switching amplifier of class D, E, F or any combinations thereof. Combining Equations (1) and (2), the impedance matching conditions for this network are

$$R_I(\omega)=F_R(\mathrm{dc})/\omega C_a, X_I(\omega)=F_x(\mathrm{dc})/\omega C_a \quad (3).$$

[0140] In some examples of a tunable switching amplifier, one tunable element may be the capacitance C_a, which may be tuned by tuning the external capacitors placed in parallel with the switching elements.

[0141] In some examples of a tunable switching amplifier, one tunable element may be the duty cycle dc of the ON switch-state of the switching elements of the amplifier. Adjusting the duty cycle, dc, via Pulse Width Modulation (PWM) has been used in switching amplifiers to achieve output power control. In this specification, we disclose that PWM may also be used to achieve impedance matching, namely to satisfy Eqs.(3), and thus maximize the amplifier efficiency.

[0142] In some examples of a tunable switching amplifier one tunable element may be the switching frequency, which is also the driving frequency of the IMN+load network and may be designed to be substantially close to the resonant frequency of the IMN+load network. Tuning the switching frequency may change the characteristic impedance of the amplifier and the impedance of the IMN+load network. The switching frequency of the amplifier may be tuned appropriately together with one more tunable parameters, so that Eqs.(3) are satisfied.

[0143] A benefit of tuning the duty cycle and/or the driving frequency of the amplifier for dynamic impedance matching is that these parameters can be tuned electronically, quickly, and over a broad range. In contrast, for example, a tunable capacitor that can sustain a large voltage and has a large enough tunable range and quality factor may be expensive, slow or unavailable for with the necessary component specifications

[0144] Examples of Methods for Tunable Impedance Matching of a Variable Load

[0145] A simplified circuit diagram showing the circuit level structure of a class D power amplifier **802**, impedance matching network **804** and an inductive load **806** is shown in FIG. **8**. The diagram shows the basic components of the system with the switching amplifier **804** comprising a power source **810**, switching elements **808**, and capacitors. The impedance matching network **804** comprising inductors and capacitors, and the load **806** modeled as an inductor and a resistor.

[0146] An exemplary embodiment of this inventive tuning scheme comprises a half-bridge class-D amplifier operating at switching frequency f and driving a low-loss inductive element R+jωL via an IMN, as shown in FIG. **8**.

[0147] In some embodiments L' may be tunable. L' may be tuned by a variable tapping point on the inductor or by connecting a tunable capacitor in series or in parallel to the inductor. In some embodiments C_a may be tunable. For the

half bridge topology, C_a may be tuned by varying either one or both capacitors C_{switch}, as only the parallel sum of these capacitors matters for the amplifier operation. For the full bridge topology, C_a may be tuned by varying either one, two, three or all capacitors C_{switch}, as only their combination (series sum of the two parallel sums associated with the two halves of the bridge) matters for the amplifier operation.

[0148] In some embodiments of tunable impedance matching, two of the components of the IMN may be tunable. In some embodiments, L' and C_2 may be tuned. Then, FIG. **9** shows the values of the two tunable components needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier, for f=250 kHz, dc=40%, C_a=640 pF and C_1=10 nF. Since the IMN always adjusts to the fixed characteristic impedance of the amplifier, the output power is always constant as the inductive element is varying.

[0149] In some embodiments of tunable impedance matching, elements in the switching amplifier may also be tunable. In some embodiments the capacitance C_a along with the IMN capacitor C_2 may be tuned. Then, FIG. **10** shows the values of the two tunable components needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for f=250 kHz, dc=40%, C_1=10 nF and ωL'=1000Ω. It can be inferred from FIG. **10** that C_2 needs to be tuned mainly in response to variations in L and that the output power decreases as R increases.

[0150] In some embodiments of tunable impedance matching, the duty cycle dc along with the IMN capacitor C_2 may be tuned. Then, FIG. **11** shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for f=250 kHz, C_a=640 pF, C_1=10 nF and ωL'=100052. It can be inferred from FIG. **11** that C_2 needs to be tuned mainly in response to variations in L and that the output power decreases as R increases.

[0151] In some embodiments of tunable impedance matching, the capacitance C_a along with the IMN inductor L' may be tuned. Then, FIG. **11**A shows the values of the two tunable components needed to achieve impedance matching as functions of the varying R of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for f=250 kHz, dc=40%, C_1=10 nF and C_2=7.5 nF. It can be inferred from FIG. **11**A that the output power decreases as R increases.

[0152] In some embodiments of tunable impedance matching, the duty cycle dc along with the IMN inductor L' may be tuned. Then, FIG. **11**B shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for f=250 kHz, C_a=640 pF, C_1=10 nF and C_2=7.5 nF as functions of the varying R of the inductive element. It can be inferred from FIG. **11**B that the output power decreases as R increases.

[0153] In some embodiments of tunable impedance matching, only elements in the switching amplifier may be tunable with no tunable elements in the IMN. In some embodiments the duty cycle dc along with the capacitance C_a may be tuned. Then, FIG. **11**C, shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for f=250 kHz, C_1=10 nF, C_2=7.5 nF and ωL'=1000Ω. It can be inferred from FIG. **11**C that the output power is a non-monotonic function of R. These embodiments may be able to achieve dynamic impedance matching when variations in L (and thus the resonant frequency) are modest.

[0154] In some embodiments, dynamic impedance matching with fixed elements inside the IMN, also when L is varying greatly as explained earlier, may be achieved by varying the driving frequency of the external frequency f (e.g. the switching frequency of a switching amplifier) so that it follows the varying resonant frequency of the resonator. Using the switching frequency f and the switch duty cycle dc as the two variable parameters, full impedance matching can be achieved as R and L are varying without the need of any variable components. Then, FIG. **12** shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for C_a=640 pF, C_1=10 nF, C_2=7.5 nF and L'=637 μH. It can be inferred from FIG. **12** that the frequency f needs to be tuned mainly in response to variations in L, as explained earlier.

[0155] Tunable Impedance Matching for Systems of Wireless Power Transmission

[0156] In applications of wireless power transfer the low-loss inductive element may be the coil of a source resonator coupled to one or more device resonators or other resonators, such as repeater resonators, for example. The impedance of the inductive element R+jωL may include the reflected impedances of the other resonators on the coil of the source resonator. Variations of R and L of the inductive element may occur due to external perturbations in the vicinity of the source resonator and/or the other resonators or thermal drift of components. Variations of R and L of the inductive element may also occur during normal use of the wireless power transmission system due to relative motion of the devices and other resonators with respect to the source. The relative motion of these devices and other resonators with respect to the source, or relative motion or position of other sources, may lead to varying coupling (and thus varying reflected impedances) of the devices to the source. Furthermore, variations of R and L of the inductive element may also occur during normal use of the wireless power transmission system due to changes within the other coupled resonators, such as changes in the power draw of their loads. All the methods and embodiments disclosed so far apply also to this case in order to achieve dynamic impedance matching of this inductive element to the external circuit driving it.

[0157] To demonstrate the presently disclosed dynamic impedance matching methods for a wireless power transmission system, consider a source resonator including a low-loss source coil, which is inductively coupled to the device coil of a device resonator driving a resistive load.

[0158] In some embodiments, dynamic impedance matching may be achieved at the source circuit. In some embodiments, dynamic impedance matching may also be achieved at the device circuit. When full impedance matching is obtained (both at the source and the device), the effective resistance of the source inductive element (namely the resistance of the source coil R_s plus the reflected impedance from the device) is $R=R_s\sqrt{1+U_{sd}^2}$. (Similarly the effective resistance of the

device inductive element is $R_d\sqrt{1+U_{sd}^2}$, where R_d is the resistance of the device coil.) Dynamic variation of the mutual inductance between the coils due to motion results in a dynamic variation of $U_{sd}=\omega M_{sd}/\sqrt{R_s R_d}$. Therefore, when both source and device are dynamically tuned, the variation of mutual inductance is seen from the source circuit side as a variation in the source inductive element resistance R. Note that in this type of variation, the resonant frequencies of the resonators may not change substantially, since L may not be changing. Therefore, all the methods and examples presented for dynamic impedance matching may be used for the source circuit of the wireless power transmission system.

[0159] Note that, since the resistance R represents both the source coil and the reflected impedances of the device coils to the source coil, in FIGS. **9-12**, as R increases due to the increasing U, the associated wireless power transmission efficiency increases. In some embodiments, an approximately constant power may be required at the load driven by the device circuitry. To achieve a constant level of power transmitted to the device, the required output power of the source circuit may need to decrease as U increases. If dynamic impedance matching is achieved via tuning some of the amplifier parameters, the output power of the amplifier may vary accordingly. In some embodiments, the automatic variation of the output power is preferred to be monotonically decreasing with R, so that it matches the constant device power requirement. In embodiments where the output power level is accomplished by adjusting the DC driving voltage of the power generator, using an impedance matching set of tunable parameters which leads to monotonically decreasing output power vs. R will imply that constant power can be kept at the power load in the device with only a moderate adjustment of the DC driving voltage. In embodiments, where the "knob" to adjust the output power level is the duty cycle dc or the phase of a switching amplifier or a component inside an Impedance Matching Network, using an impedance matching set of tunable parameters which leads to monotonically decreasing output power vs. R will imply that constant power can be kept at the power load in the device with only a moderate adjustment of this power "knob".

[0160] In the examples of FIGS. **9-12**, if $R_s=0.19\Omega$, then the range R=**0.2–2**Ω corresponds approximately to $U_{sd}=0.3$–10.5. For these values, in FIG. **14**, we show with dashed lines the output power (normalized to DC voltage squared) required to keep a constant power level at the load, when both source and device are dynamically impedance matched. The similar trend between the solid and dashed lines explains why a set of tunable parameters with such a variation of output power may be preferable.

[0161] In some embodiments, dynamic impedance matching may be achieved at the source circuit, but impedance matching may not be achieved or may only partially be achieved at the device circuit. As the mutual inductance between the source and device coils varies, the varying reflected impedance of the device to the source may result in a variation of both the effective resistance R and the effective inductance L of the source inductive element. The methods presented so far for dynamic impedance matching are applicable and can be used for the tunable source circuit of the wireless power transmission system.

[0162] As an example, consider the circuit of FIG. **14**, where f=250 kHz, C_a=640 pF, R_s=0.19Ω, L_s=100 μH, C_{1s}=10 nF, $\omega L'_s$=1000Ω, R_d=0.3Ω, L_d=40 μH, C_{1d}=87.5 nF, C_{2d}=13 nF, $\omega L'_d$=400Ω and Z_l=50Ω, where s and d denote the source and device resonators respectively and the system is matched at U_{sd}=3. Tuning the duty cycle dc of the switching amplifier and the capacitor C_{2s} may be used to dynamically impedance match the source, as the non-tunable device is moving relatively to the source changing the mutual inductance M between the source and the device. In FIG. **14**, we show the required values of the tunable parameters along with the output power per DC voltage of the amplifier. The dashed line again indicates the output power of the amplifier that would be needed so that the power at the load is a constant value.

[0163] In some embodiments, tuning the driving frequency f of the source driving circuit may still be used to achieve dynamic impedance matching at the source for a system of wireless power transmission between the source and one or more devices. As explained earlier, this method enables full dynamic impedance matching of the source, even when there are variations in the source inductance L_s and thus the source resonant frequency. For efficient power transmission from the source to the devices, the device resonant frequencies must be tuned to follow the variations of the matched driving and source-resonant frequencies. Tuning a device capacitance (for example, in the embodiment of FIG. **13** C_{1d} or C_{2d}) may be necessary, when there are variations in the resonant frequency of either the source or the device resonators. In fact, in a wireless power transfer system with multiple sources and devices, tuning the driving frequency alleviates the need to tune only one source-object resonant frequency, however, all the rest of the objects may need a mechanism (such as a tunable capacitance) to tune their resonant frequencies to match the driving frequency.

[0164] Resonator Thermal Management

[0165] In wireless energy transfer systems, some portion of the energy lost during the wireless transfer process is dissipated as heat. Energy may be dissipated in the resonator components themselves. For example, even high-Q conductors and components have some loss or resistance, and these conductors and components may heat up when electric currents and/or electromagnetic fields flow through them. Energy may be dissipated in materials and objects around a resonator. For example, eddy currents dissipated in imperfect conductors or dielectrics surrounding or near-by the resonator may heat up those objects. In addition to affecting the material properties of those objects, this heat may be transferred through conductive, radiative, or convective processes to the resonator components. Any of these heating effects may affect the resonator Q, impedance, frequency, etc., and therefore the performance of the wireless energy transfer system.

[0166] In a resonator comprising a block or core of magnetic material, heat may be generated in the magnetic material due to hysteresis losses and to resistive losses resulting from induced eddy currents. Both effects depend on the magnetic flux density in the material, and both can create significant amounts of heat, especially in regions where the flux density or eddy currents may be concentrated or localized. In addition to the flux density, the frequency of the oscillating magnetic field, the magnetic material composition and losses, and the ambient or operating temperature of the magnetic material may all impact how hysteresis and resistive losses heat the material.

[0167] In embodiments, the properties of the magnetic material such as the type of material, the dimensions of the block, and the like, and the magnetic field parameters may be chosen for specific operating power levels and environments to minimize heating of the magnetic material. In some

embodiments, changes, cracks, or imperfections in a block of magnetic material may increase the losses and heating of the magnetic material in wireless power transmission applications.

[0168] For magnetic blocks with imperfections, or that are comprised of smaller size tiles or pieces of magnetic material arranged into a larger unit, the losses in the block may be uneven and may be concentrated in regions where there are inhomogeneities or relatively narrow gaps between adjacent tiles or pieces of magnetic material. For example, if an irregular gap exists in a magnetic block of material, then the effective reluctance of various magnetic flux paths through the material may be substantially irregular and the magnetic field may be more concentrated in portions of the block where the magnetic reluctance is lowest. In some cases, the effective reluctance may be lowest where the gap between tiles or pieces is narrowest or where the density of imperfections is lowest. Because the magnetic material guides the magnetic field, the magnetic flux density may not be substantially uniform across the block, but may be concentrated in regions offering relatively lower reluctance. Irregular concentrations of the magnetic field within a block of magnetic material may not be desirable because they may result in uneven losses and heat dissipation in the material.

[0169] For example, consider a magnetic resonator comprising a conductor **1506** wrapped around a block of magnetic material composed of two individual tiles **1502**, **1504** of magnetic material joined such that they form a seam **1508** that is perpendicular to the axis of the conductor **1506** loops as depicted in FIG. **15**. An irregular gap in the seam **1508** between the tiles of magnetic material **1502**, **1504** may force the magnetic field **1512** (represented schematically by the dashed magnetic field lines) in the resonator to concentrate in a sub region **1510** of the cross section of the magnetic material. Since the magnetic field will follow the path of least reluctance, a path including an air gap between two pieces of magnetic material may create an effectively higher reluctance path than one that traverses the width of the magnetic material at a point where the pieces of magnetic materials touch or have a smaller air gap. The magnetic flux density may therefore preferentially flow through a relatively small cross area of the magnetic material resulting in a high concentration of magnetic flux in that small area **1510**.

[0170] In many magnetic materials of interest, more inhomogeneous flux density distributions lead to higher overall losses. Moreover, the more inhomogeneous flux distribution may result in material saturation and cause localized heating of the area in which the magnetic flux is concentrated. The localized heating may alter the properties of the magnetic material, in some cases exacerbating the losses. For example, in the relevant regimes of operation of some materials, hysteresis and resistive losses increase with temperature. If heating the material increases material losses, resulting in more heating, the temperature of the material may continue to increase and even runaway if no corrective action is taken. In some instances, the temperature may reach 100 C or more and may degrade the properties of the magnetic material and the performance of wireless power transfer. In some instances, the magnetic materials may be damaged, or the surrounding electronic components, packaging and/or enclosures may be damaged by the excessive heat.

[0171] In embodiments, variations or irregularities between tiles or pieces of the block of magnetic material may be minimized by machining, polishing, grinding, and the like, the edges of the tiles or pieces to ensure a tight fit between tiles of magnetic materials providing a substantially more uniform reluctance through the whole cross section of the block of magnetic material. In embodiments, a block of magnetic material may require a means for providing a compression force between the tiles to ensure the tiles are pressed tight together without gaps. In embodiments, an adhesive may be used between the tiles to ensure they remain in tight contact.

[0172] In embodiments the irregular spacing of adjacent tiles of magnetic material may be reduced by adding a deliberate gap between adjacent tiles of magnetic material. In embodiments a deliberate gap may be used as a spacer to ensure even or regular separations between magnetic material tiles or pieces. Deliberate gaps of flexible materials may also reduce irregularities in the spacings due to tile movement or vibrations. In embodiments, the edges of adjacent tiles of magnetic material may be taped, dipped, coated, and the like with an electrical insulator, to prevent eddy currents from flowing through reduced cross-sectional areas of the block, thus lowering the eddy current losses in the material. In embodiments a separator may be integrated into the resonator packaging. The spacer may provide a spacing of 1 mm or less.

[0173] In embodiments, the mechanical properties of the spacer between tiles may be chosen so as to improve the tolerance of the overall structure to mechanical effects such as changes in the dimensions and/or shape of the tiles due to intrinsic effects (e.g, magnetostriction, thermal expansion, and the like) as well as external shocks and vibrations. For example, the spacer may have a desired amount of mechanical give to accommodate the expansion and/or contraction of individual tiles, and may help reduce the stress on the tiles when they are subjected to mechanical vibrations, thus helping to reduce the appearance of cracks and other defects in the magnetic material.

[0174] In embodiments, it may be preferable to arrange the individual tiles that comprise the block of magnetic material to minimize the number of seams or gaps between tiles that are perpendicular to the dipole moment of the resonator. In embodiments it may be preferable to arrange and orient the tiles of magnetic material to minimize the gaps between tiles that are perpendicular to the axis formed by the loops of a conductor comprising the resonator.

[0175] For example, consider the resonator structure depicted in FIG. **16**. The resonator comprises a conductor **1604** wrapped around a block of magnetic material comprising six separate individual tiles **1602** arranged in a three by two array. The arrangement of tiles results in two tile seams **1606**, **1608** when traversing the block of magnetic material in one direction, and only one tile seam **1610** when traversing the block of magnetic material in the orthogonal direction. In embodiments, it may be preferable to wrap the conductor wire **1604** around the block of magnetic material such that the dipole moment of the resonator is perpendicular to the fewest number of tile seams. The inventors have observed that there is relatively less heating induced around seams and gaps **1606**, **1608** that are parallel to the dipole moment of the resonator. Seams and gaps that run perpendicular to the dipole moment of the resonator may also be referred to as critical seams or critical seam areas. It may still be desirable, however, to electrically insulate gaps that run parallel to the dipole moment of the resonator (such as **1606** and **1608**) so as to reduce eddy current losses. Uneven contact between tiles

separated by such parallel gaps may cause eddy currents to flow through narrow contact points, leading to large losses at such points.

[0176] In embodiments, irregularities in spacing may be tolerated with adequate cooling of the critical seam areas to prevent the localized degradation of material properties when the magnetic material heats up. Maintaining the temperature of the magnetic material below a critical temperature may prevent a runaway effect caused by a sufficiently high temperature. With proper cooling of the critical seam area, the wireless energy transfer performance may be satisfactory despite the additional loss and heating effects due to irregular spacing, cracks, or gaps between tiles.

[0177] Effective heatsinking of the resonator structure to prevent excessive localized heating of the magnetic material poses several challenges. Metallic materials that are typically used for heatsinks and thermal conduction can interact with the magnetic fields used for wireless energy transfer by the resonators and affect the performance of the system. Their location, size, orientation, and use should be designed so as to not excessively lower the perturbed Q of the resonators in the presence of these heatsinking materials. In addition, owing to the relatively poor thermal conductivity of magnetic materials such as ferrites, a relatively large contact area between the heatsink and the magnetic material may be required to provide adequate cooling which may require placement of substantial amount of lossy materials close to the magnetic resonator.

[0178] In embodiments, adequate cooling of the resonator may be achieved with minimal effect on the wireless energy transfer performance with strategic placement of thermally conductive materials. In embodiments, strips of thermally conductive material may be placed in between loops of conductor wire and in thermal contact with the block of magnetic material.

[0179] One exemplary embodiment of a resonator with strips of thermally conductive material is depicted in FIG. **17**. FIG. **17**A shows the resonator structure without the conducting strips and with the block of magnetic material comprising smaller tiles of magnetic material forming gaps or seams. Strips of thermally conductive **1708** material may be placed in between the loops of the conductor **1702** and in thermal contact with the block of magnetic material **1704** as depicted in FIGS. **17**B and **17**C. To minimize the effects of the strips on the parameters of the resonator, in some embodiments it may be preferable to arrange the strips parallel to the loops of conductor or perpendicular to the dipole moment of the resonator. The strips of conductor may be placed to cover as much or as many of the seams or gaps between the tiles as possible especially the seams between tiles that are perpendicular to the dipole moment of the resonator.

[0180] In embodiments the thermally conductive material may comprise copper, aluminum, brass, thermal epoxy, paste, pads, and the like, and may be any material that has a thermal conductivity that is at least that of the magnetic material in the resonator (~5 W/(K-m) for some commercial ferrite materials). In embodiments where the thermally conductive material is also electrically conducting, the material may require a layer or coating of an electrical insulator to prevent shorting and direct electrical contact with the magnetic material or the loops of conductor of the resonator.

[0181] In embodiments the strips of thermally conductive material may be used to conduct heat from the resonator structure to a structure or medium that can safely dissipate the thermal energy. In embodiments the thermally conductive strips may be connected to a heat sink such as a large plate located above the strips of conductor that can dissipate the thermal energy using passive or forced convection, radiation, or conduction to the environment. In embodiments the system may include any number of active cooling systems that may be external or internal to the resonator structure that can dissipate the thermal energy from the thermally conducting strips and may include liquid cooling systems, forced air systems, and the like. For example, the thermally conducting strips may be hollow or comprise channels for coolant that may be pumped or forced through to cool the magnetic material. In embodiments, a field deflector made of a good electrical conductor (such as copper, silver, aluminum, and the like) may double as part of the heatsinking apparatus. The addition of thermally and electrically conducting strips to the space between the magnetic material and the field deflector may have a marginal effect on the perturbed Q, as the electromagnetic fields in that space are typically suppressed by the presence of the field deflector. Such conducting strips may be thermally connected to both the magnetic material and the field deflector to make the temperature distribution among different strips more homogeneous.

[0182] In embodiments the thermally conducting strips are spaced to allow at least one loop of conductor to wrap around the magnetic material. In embodiments the strips of thermally conductive material may be positioned only at the gaps or seams of the magnetic material. In other embodiments, the strips may be positioned to contact the magnetic material at substantially throughout its complete length. In other embodiments, the strips may be distributed to match the flux density within the magnetic material. Areas of the magnetic material which under normal operation of the resonator may have higher magnetic flux densities may have a higher density of contact with the thermally conductive strips. In embodiments depicted in FIG. **17**A) for example, the highest magnetic flux density in the magnetic material may be observed toward the center of the block of magnetic material and the lower density may be toward the ends of the block in the direction of the dipole moment of the resonator.

[0183] To show how the use of thermally conducting strips helps to reduce the overall temperature in the magnetic material as well as the temperature at potential hot spots, the inventors have performed a finite element simulation of a resonator structure similar to that depicted in FIG. **17**C. The structure was simulated operating at a frequency of 235 kHz and comprising a block of EPCOS N95 magnetic material measuring 30 cm×30 cm×5 mm excited by 10 turns of litz wire (symmetrically placed at 25 mm, 40 mm, 55 mm, 90 mm and 105 mm from the plane of symmetry of the structure) carrying 40 A of peak current each, and thermally connected to a 50 cm×50 cm×4 mm field deflector by means of three 3×¾×1' hollow square tubes (⅛" wall thickness) of aluminum (alloy 6063) whose central axes are placed at −75 mm, 0 mm, and +75 from the symmetry plane of the structure. The perturbed Q due to the field deflector and hollow tubes was found to be 1400 (compared to **1710** for the same structure without the hollow tubes). The power dissipated in the shield and tubes was calculated to be 35.6 W, while that dissipated in the magnetic material was 58.3 W. Assuming the structure is cooled by air convection and radiation and an ambient temperature of 24° C., the maximum temperature in the structure was 85° C. (at points in the magnetic material approximately halfway between the hollow tubes) while the temperature in

parts of the magnetic material in contact with the hollow tubes was approximately 68° C. By comparison, the same resonator without the thermally conducting hollow tubes dissipated 62.0 W in the magnetic material for the same excitation current of 40 W peak and the maximum temperature in the magnetic material was found to be 111° C.

[0184] The advantage of the conducting strips is more apparent still if we introduce a defect in a portion of the magnetic material that is in good thermal contact with the tubes. An air gap 10 cm long and 0.5 mm placed at the center of the magnetic material and oriented perpendicular to the dipole moment increases the power dissipated in the magnetic material to 69.9 W (the additional 11.6 W relative to the previously discussed no-defect example being highly concentrated in the vicinity of the gap), but the conducting tube ensures that the maximum temperature in the magnetic material has only a relative modest increase of 11° C. to 96° C. In contrast, the same defect without the conducting tubes leads to a maximum temperature of 161° C. near the defect. Cooling solutions other than convection and radiation, such as thermally connecting the conducting tubes body with large thermal mass or actively cooling them, may lead to even lower operational temperatures for this resonator at the same current level.

[0185] In embodiments thermally conductive strips of material may be positioned at areas that may have the highest probability of developing cracks that may cause irregular gaps in the magnetic material. Such areas may be areas of high stress or strain on the material, or areas with poor support or backing from the packaging of the resonator. Strategically positioned thermally conductive strips may ensure that as cracks or irregular gaps develop in the magnetic material, the temperature of the magnetic material will be maintained below its critical temperature. The critical temperature may be defined as the Curie temperature of the magnetic material, or any temperature at which the characteristics of the resonator have been degraded beyond the desired performance parameters.

[0186] In embodiments the heastsinking structure may provide mechanical support to the magnetic material. In embodiments the heatsinking structure may be designed to have a desired amount of mechanical give (e.g., by using epoxy, thermal pads, and the like having suitable mechanical properties to thermally connect different elements of the structure) so as to provide the resonator with a greater amount of tolerance to changes in the intrinsic dimensions of its elements (due to thermal expansion, magnetostriction, and the like) as well as external shocks and vibrations, and prevent the formation of cracks and other defects.

[0187] In embodiments where the resonator comprises orthogonal windings wrapped around the magnetic material, the strips of conducting material may be tailored to make thermal contact with the magnetic material within areas delimited by two orthogonal sets of adjacent loops. In embodiments a strip may contain appropriate indentations to fit around the conductor of at least one orthogonal winding while making thermal contact with the magnetic material at least one point. In embodiments the magnetic material may be in thermal contact with a number of thermally conducting blocks placed between adjacent loops. The thermally conducting blocks may be in turn thermally connected to one another by means of a good thermal conductor and/or heatsinked.

[0188] Throughout this description although the term thermally conductive strips of material was used as an exemplary specimen of a shape of a material it should be understood by those skilled in the art that any shapes and contours may be substituted without departing from the spirit of the inventions. Squared, ovals, strips, dots, elongated shapes, and the like would all be within the spirit of the present invention.

[0189] Communication in a Wireless Energy Transfer System

[0190] A wireless energy transfer system may require a verification step to ensure that energy is being transferred between designated resonators. For example, in wireless energy transfer systems, source resonators, device resonators, and repeater resonators, do not require physical contact with each other in order to exchange energy, and these resonators may be separated from each other by distances of centimeters or meters, depending on the size and number of resonators in the system. In some configurations, multiple resonators may be in a position to generate or receive power, but only two or some of those resonators are designated resonators.

[0191] Communication of information between resonators in a wireless energy transfer system may be utilized to designate resonators. Communication of information between resonators may be implemented using in-band or out-of-band communications or communications channels. If at least some part of a magnetic resonator used to exchange power is also used to exchange information, and the carrier frequency of the information exchange is close to the resonant frequency used in the power exchange, we refer to that communication as in-band. Any other type of communication between magnetic resonators is referred to as out-of-band. An out-of-band communication channel may use an antenna and a signaling protocol that is separated from the energy transfer resonator and magnetic fields. An out-of-band communication channel may use or be based on Bluetooth, WiFi, Zigbee, NFC technology and the like.

[0192] Communication between resonators may be used to coordinate the wireless energy transfer or to adjust the parameters of a wireless energy transfer system, to identify and authenticate available power sources and devices, to optimize efficiency, power delivery, and the like, to track and bill energy preferences, usage, and the like, and to monitor system performance, battery condition, vehicle health, extraneous objects, also referred to as foreign objects, and the like. Methods for designating and verifying resonators for energy transfer may be different when in-band and out-of-band communication channels are used because the distance over which communication signals may be exchanged using out-of-band techniques may greatly exceed the distance over which the power signals may be exchanged. Also, the bandwidth of out-of-band communication signals may be larger than in-band communication signals. This difference in communication range and capability may affect the coordination of the wireless energy transfer system. For example, the number of resonators that may be addressed using out-of-band communication may be very large and communicating resonators may be farther apart than the distance over which they may efficiently exchange energy.

[0193] In some embodiments all of the signaling and communication may be performed using an in-band communication channel and the signals may be modulated on the fields used for energy transfer. In other embodiments, in-band communication may use substantially the same frequency spectrum as is used for energy transfer, but communication may

occur while useful amounts of energy are not being transmitted. Using only the in-band communication channel may be preferable if separate or multiple verification steps are problematic, because the range of the communication may be limited to the same range as the power exchange or because the information arrives as a modulation on the power signal itself. In some embodiments however, a separate out-of-band communication channel may be more desirable. For example, an out-of-band communication channel may be less expensive to implement and may support higher data rates. An out-of-band communication channel may support longer distance communication, allowing resonator discovery and power system mapping. An out-of-band communication channel may operate regardless of whether or not power transfer is taking place and may occur without disruption of the power transfer.

[0194] An exemplary embodiment of a wireless energy system is shown in FIG. **18**. This exemplary embodiment comprises two device resonators **1802**, **1816** each with an out-of-band communication module **1804**, **1818** respectively and two source resonators **1806**, **1810** each with their own out-of-band communication modules **1808**, **1812** respectively. The system may use the out-of-band communication channel to adjust and coordinate the energy transfer. The communication channel may be used to discover or find resonators in the proximity, to initiate power transfer, and to communicate adjustment of operating parameters such as power output, impedance, frequency, and the like of the individual resonators.

[0195] In some situations a device resonator may incorrectly communicate with one source but receive energy from another source resonator. For example, imagine that device **1802** sends an out-of-band communication signal requesting power from a source. Source **1810** may respond and begin to supply power to device **1802**. Imagine that device **1816** also sends an out-of-band communication signal requesting power from a source and that source **1806** responds and begins to supply power to device **1816**. Because of the proximity of device **1802** to source **1806**, it is possible that device **1802** receives some or most of its power from source **1806**. If the power level received by device **1802** becomes too high, device **1802** may send an out-of-band communication signal to source **1810** to reduce the power it is transmitting to device **1802**. However, device **1802** may still be receiving too much power, because it is receiving power from source **1806** but is not communicating control signals to that source **1806**.

[0196] Therefore, the separation of the energy transfer channel and the communication channel may create performance, control, safety, security, reliability, and the like issues in wireless energy transfer systems. In embodiments, it may be necessary for resonators in a wireless energy transfer system to identify/designate and verify any and all resonators with which it is exchanging power. As those skilled in the art will recognize, the example shown in FIG. **18** is just one example and there exist many configurations and arrangements of wireless power transmission systems that may benefit from explicit or implicit energy transfer verification steps.

[0197] In embodiments, the potential performance, control, safety, security, reliability and the like, issues may be avoided by providing at least one verification step that insures that the energy transfer channel and the communication channel used by a pair of resonators are associated with the same pair of resonators.

[0198] In embodiments the verification step may comprise some additional information exchange or signaling through the wireless energy transfer channel. A verification step comprising communication or information exchange using the energy transfer channel, or fields of the energy transfer channel may be used to verify that the out-of-band communication channel is exchanging information between the same two resonators that are or will be exchanging energy.

[0199] In embodiments with an out-of-band communication channel the verification step may be implicit or explicit. In some embodiments verification may be implicit. In embodiments an energy transfer channel may be implicitly verified by monitoring and comparing the behavior of the energy transfer channel to expected behavior or parameters in response to the out-of-band information exchange. For example, after establishing out-of-band communications, a device may request that a wireless source increase the amount of power it is transmitting. At the same time, parameters of the wireless energy transfer channel and resonators may be monitored. An observed increase of delivered power at the device may be used to infer that the out-of-band communication channel and the energy transfer channel are correctly linked to the designated resonators.

[0200] In embodiments an implicit verification step may involve monitoring any number of the parameters of the wireless energy transfer or parameters of the resonators and components used in the wireless energy transfer. In embodiments the currents, voltages, impedances, frequency, efficiency, temperatures, of the resonators and their drive circuits and the like may be monitored and compared to expected values, trends, changes and the like as a result of an out-of-band communication exchange.

[0201] In embodiments a resonator may store tables of measured parameters and expected values, trends, and/or changes to these parameters as a consequence of a communication exchange. A resonator may store a history of communications and observed parameter changes that may be used to verify the energy transfer channel. In some cases a single unexpected parameter change due to a communication exchange may be not be conclusive enough to determine the out-of-band channel is incorrectly paired. In some embodiments the history of parameter changes may be scanned or monitored over several or many communication exchanges to perform verification.

[0202] An example algorithm showing the series of steps which may be used to implicitly verify an energy transfer channel in a wireless energy transfer system using out-of-band communication is shown in FIG. **19**A. In the first step **1902** an out-of-band communication channel between a source and a device is established. In the next step **1904** the source and device may exchange information regarding adjusting the parameters of the wireless energy transfer or parameters of the components used for wireless energy transfer. The information exchange on the out-of-band communication channel may be a normal exchange used in normal operation of the system to control and adjust the energy transfer. In some systems the out-of-band communication channel may be encrypted preventing eavesdropping, impersonation, and the like. In the next step **1906** the source and the device or just a source or just a device may monitor and keep track of any changes to the parameters of the wireless energy transfer or any changes in parameters in the components used in the energy transfer. The tracked changes may be compared against expected changes to the parameters as a consequence

of any out-of-band communication exchanges. Validation may be considered failed when one or many observed changes in parameters do not correspond to expected changes in parameters.

[0203] In some embodiments of wireless energy transfer systems verification may be explicit. In embodiments a source or a device may alter, dither, modulate, and the like the parameters of the wireless energy transfer or the parameters of the resonators used in the wireless energy transfer to communicate or provide a verifiable signal to a source or device through the energy transfer channel. The explicit verification may involve changing, altering, modulating, and the like some parameters of the wireless energy transfer or the parameters of the resonators and components used in the energy transfer for the explicit purpose of verification and may not be associated with optimizing, tuning, or adjusting the energy transfer.

[0204] The changing, altering, modulating, and the like some parameters of the wireless energy transfer or the parameters of the resonators and components used in the energy transfer for the purpose of signaling or communicating with another wireless energy resonator or component may also be referred to as in-band communication. In embodiments, the in-band communication channel may be implemented as part of the wireless energy transfer resonators and components. Information may be transmitted from one resonator to another by changing the parameters of the resonators. Parameters such as inductance, impedance, resistance, and the like may be dithered or changed by one resonator. These changes may affect the impedance, resistance, or inductance of other resonators around the signaling resonator. The changes may manifest themselves as corresponding dithers of voltage, current, and the like on the resonators which may be detected and decoded into messages. In embodiments, in-band communication may comprise altering, changing, modulating, and the like the power level, amplitude, phase, orientation, frequency, and the like of the magnetic fields used for energy transfer.

[0205] In one embodiment the explicit in-band verification may be performed after an out-of-band communication channel has been established. Using the out-of-band communication channel a source and a device may exchange information as to the power transfer capabilities and in-band signaling capabilities. Wireless energy transfer between a source and a device may then be initiated. The source or device may request or challenge the other source or device to signal using the in-band communication channel to verify the connection between the out-of-band and communication channel and the energy transfer channel. The channel is verified when the agreed signaling established in the out-of-band communication channel is observed at the in-band communication channel.

[0206] In embodiments verification may be performed only during specific or predetermined times of an energy exchange protocol such as during energy transfer startup. In other embodiments explicit verification steps may be performed periodically during the normal operation of the wireless energy transfer system. The verification steps may be triggered when the efficiency or characteristics of the wireless power transfer change which may signal that the physical orientations have changed. In embodiments the communication controller may maintain a history of the energy transfer characteristics and initiate a verification of the transfer that includes signaling using the resonators when a change in the characteristics is observed. A change in the energy transfer characteristics may be observed as a change in the efficiency of the energy transfer, the impedance, voltage, current, and the like of the resonators, or components of the resonators and power and control circuitry.

[0207] Those skilled in the art will appreciate a signaling and communication channel capable of transmitting messages may be secured with any number of encryption, authentication, and security algorithms. In embodiments the out-of-band communication may be encrypted and the secured communication channel may be used to transmit random sequences for verification using the in-band channel. In embodiments the in-band communication channel may be encrypted, randomized, or secured by any known security and cryptography protocols and algorithms. The security and cryptography algorithms may be used to authenticate and verify compatibility between resonators and may use a public key infrastructure (PKI) and secondary communication channels for authorization and authentication.

[0208] In embodiments of energy transfer systems between a source and a device a device may verify the energy transfer channel to ensure it is receiving energy from the desired or assumed source. A source may verify the energy transfer channel to ensure energy is being transferred to the desired or assumed source. In some embodiments the verification may be bidirectional and a source and device may both verify their energy transfer channels in one step or protocol operation. In embodiments, there may be more than two resonators and there may be repeater resonators. In embodiments of multiple resonators, communication and control may be centralized in one or a few resonators or communication and control may be distributed across many, most, or all the resonators in a network. In embodiments, communication and/or control may be effected by one or more semiconductor chips or microcontrollers that are coupled to other wireless energy transfer components.

[0209] An example algorithm showing the series of steps which may be used to explicitly verify an energy transfer channel in a wireless energy transfer system using out-of-band communication is shown in FIG. **19**B. In the first step **1908** an out-of-band communication channel between a source and a device is established. In the next step **1910** the source and device may coordinate or agree on a signaling protocol, method, scheme, and the like that may be transmitted through the wireless energy transfer channel. To prevent eavesdropping and provide security the out-of-band communication channel may be encrypted and the source and device may follow any number of known cryptographic authentication protocols. In a system enabled with cryptographic protocols the verification code may comprise a challenge-response type exchange which may provide an additional level of security and authentication capability. A device, for example, may challenge the source to encrypt a random verification code which it sends to the source via the out-of-band communication channel using a shared secret encryption key or a private key. The verification code transmitted in the out-of-band communication channel may then be signaled **1912** through the in-band communication channel. In the case where the source and device are enabled with cryptographic protocols the verification code signaled in the in-band communication channel may be encrypted or modified by the sender with a reversible cryptographic function allowing the receiver to further authenticate the sender and verify that the

in-band communication channels are linked with the same source or device associated with the out-of-band communication channel.

[0210] In situations when the verification fails a wireless energy transfer system may try to repeat the validation procedure. In some embodiments the system may try to re-validate the wireless energy transfer channel by exchanging another verification sequence for resignaling using the in-band communication channel. In some embodiments the system may change or alter the sequence or type of information that is used to verify the in-band communication channel after attempts to verify the in-band communication channel have failed. The system may change the type of signaling, protocol, length, complexity and the like of the in-band communication verification code.

[0211] In some embodiments, upon failure of verification of the in-band communication channel and hence the energy transfer channel, the system may adjust the power level, the strength of modulation, frequency of modulation and the like of the signaling method in the in-band communication channel. For example, upon failure of verification of a source by a device, the system may attempt to perform the verification at a higher energy transfer level. The system may increase the power output of the source generating stronger magnetic fields. In another example, upon failure of verification of a source by a device, the source that communicated the verification code to the device by changing the impedance of its source resonator may increase or even double the amount of change in the impedance of the source resonator for the signaling.

[0212] In embodiments, upon failure of verification of the energy transfer channel, the system may try to probe, find, or discover other possible sources or devices using the out-of-band communication channel. In embodiments the out-of-band communication channel may be used to find other possible candidates for wireless energy transfer. In some embodiments the system may change or adjust the output power or the range of the out-of-band communication channel to help minimize false pairings.

[0213] The out-of-band communication channel may be power modulated to have several modes, long range mode to detect sources and a short range or low power mode to ensure the communication is with another device or source that is within a specified distance. In embodiments the out-of-band communication channel may be matched to the range of the wireless channel for each application. After failure of verification of the energy transfer channel the output power of the out-of-band communication channel may be slowly increased to find other possible sources or devices for wireless energy transfer. As discussed above, an out-of-band communication channel may exhibit interferences and obstructions that may be different from the interferences and obstructions of the energy transfer channel and sources and devices that may require higher power levels for out-of-band communication may be in close enough proximity to allow wireless energy transfer.

[0214] In some embodiments the out-of-band communication channel may be directed, arranged, focused, and the like, using shielding or positioning to be only effective in a confined area (i.e., under a vehicle), to insure it is only capable of establishing communication with another source or device that is in close enough proximity, position, and orientation for energy transfer.

[0215] In embodiments the system may use one or more supplemental sources of information to establish an out-of-band communication channel or to verify an in-band energy transfer channel. For example, during initial establishment of an out-of-band communication channel the locations of the sources or devices may be compared to known or mapped locations or a database of locations of wireless sources or devices to determine the most probable pair for successful energy transfer. Out-of-band communication channel discovery may be supplemented with GPS data from one or more GPS receivers, data from positioning sensors, inertial guidance systems and the like.

[0216] It is to be understood that although example embodiments with verification were described in systems consisting of a source and device verification may be performed in systems with any number of sources, devices, or repeaters. A single source may provide verification to multiple devices. In some embodiments multiple sources may provide power to one or more devices concurrently each may be varied. In embodiments verification may be performed with a repeater. In some embodiments verification may be performed through a repeater. A device receiving power from a source via a repeater resonator may verify the source of power from the repeater. A device receiving power from a source via a repeater resonator may verify the source of energy through the repeater, i.e., the in-band communication may pass through the repeater to the source for verification. It should be clear to those skilled in the art that all of these and other configurations are within the scope of the invention.

[0217] Low Resistance Electrical Conductors

[0218] As described above, resonator structures used for wireless energy transfer may include conducting wires that conduct high frequency oscillating currents. In some structures the effective resistance of the conductors may affect the quality factor of the resonator structure and a conductor with a lower loss or lower resistance may be preferable. The inventors have discovered new structures for reducing the effective resistance of conducting wires at high frequencies compared to solid wire conductors or even Litz wire conductors of the same equivalent wire gauge (diameter).

[0219] In embodiments, structures comprising concentric cylindrical conducting shells can be designed that have much lower electrical resistance for frequencies in the MHz range than similarly sized solid wire conductors or commercially available Litz wires. At such frequencies, wire resistances are dominated by skin-depth effects (also referred to as proximity effects), which prevent electrical current from being uniformly distributed over the wire cross-section. At lower frequencies, skin-depth effects may be mitigated by breaking the wire into a braid of many thin insulated wire strands (e.g. Litz wire), where the diameter of the insulated strands are related to the conductor skin depth at the operating frequency of interest. In the MHz frequency range, the skin depth for typical conductors such as copper are on the order of 10 μm, making traditional Litz wire implementations impractical.

[0220] The inventors have discovered that breaking the wire into multiple properly designed concentric insulated conducting shells can mitigate the skin depth effects for frequencies above 1 MHz. In embodiments, wires comprising fewer than 10 coaxial shells can lower AC resistance by more than a factor of 3 compared to solid wire. In embodiments, wires or conductors comprising thin concentric shells can be fabricated by a variety of processes such as electroplating,

electrodeposition, vapor deposition, sputtering, and processes that have previously been applied to the fabrication of optical fibers.

[0221] In embodiments, conducting structures comprising nested cylindrical conductors may be analyzed using the quasistatic Maxwell equations. Of particular importance in the design of these conducting structures is taking account of the proximity losses induced by each conducting shell in the others via the magnetic fields. Modeling tools may be used to optimize the number of conducting shells, the size and shape of the conducting shells, the type and thickness of insulating materials for a given conductor diameter, operating frequency and environment, cost, and the like.

[0222] One embodiment of the new conductor structure comprises a number, N, of concentric conducting shells. Such a structure can be designed to have much lower AC resistance at frequencies in the 10 MHz range than similar gauge solid or stranded wires or commercially available Litz wires.

[0223] An embodiment of a wire or conductor comprising conducting shells may comprise at least two concentric conducting shells separated by an electrical insulator. An exemplary embodiment of an electrical conductor with four concentric shells is shown in FIG. **20**. Note that the conductor may have an unlimited length along the z axis. That is, the length along the z axis is the length of the wire or the conductor. Also, the wire or conductor may have any number of bends, curves, twists, and the like (not shown) as would other conductors of equivalent gauge or thickness. Also note that in embodiments where the cross-section of the shell is annular or substantially annular, the shell will consequently be cylindrical or substantially cylindrical. There is no limitation to the shape of the cross sections and thus the shape of the resulting three-dimensional structure. For example, the cross-sectional shape may be rectangular in embodiments.

[0224] An embodiment shown in FIG. **20** comprises four concentric shells **2008**, **2006**, **2004**, **2002** of an electrical conductor that extend through the complete length of the conducting wire along the z axis. The conductor shells may be referred to by their location with respect to the center or innermost conductor shell. For convention, the innermost shell may be referred to as the first shell, and each successive shell as the second shell, third shell, etc. The successive shells may also referred to as nested concentric shells. For example, in the embodiment shown in FIG. **20** conductor shell **2002** may be referred to as the first shell or the innermost shell and the conductor **2004** as the second shell, conductor **2006** as the third shell, and conductor **2008** as the fourth shell or the outermost shell. Each shell, except the innermost and the outermost shell, is in direct proximity to two neighboring shells, an inner neighbor and an outer neighbor shell. The innermost shell only has an outer neighbor, and the outermost shell only has an inner neighbor. For example, the third conductor **2006** has two shell neighbors, the inner neighbor being the second shell **2004** and the outer neighbor being the fourth shell **2008**. In embodiments, the inner shell may be a solid core (in embodiments, cylindrical with an inner diameter zero). Alternatively, it may have a finite inner diameter and surround a core made of insulating material and the like.

[0225] In embodiments each successive shell covers its inner neighbor shell long the z axis of the conductor. Each shell wraps around its inner neighbor shell except the faces of each shell that are exposed at the ends of the conductor. For example, in the embodiment shown in FIG. **20**, shell **2002** is wrapped around by its outer neighbor shell **2004** and shell **2004** is wrapped by **2006** and etc.

[0226] In embodiments each successive shell may comprise one or more strips of conductor shaped so as to conform to the cylindrical geometry of the structure. In embodiments the strips in each shell may be mutually insulated and periodically connected to strips in adjacent shells so that the input impedances of the shells and/or strips naturally enforce the current distribution that minimizes the resistance of the structure. In embodiments the strips in each shell may be wound at a particular pitch. The pitch in different shells may be varied so as to assist in the impedance matching of the entire structure.

[0227] FIG. **20** shows an end section of the conductor with the conducting layers staggered to provide a clear illustration of the layers. The staggering of layers in the drawing should not be considered as a preferred termination of the conductor. The conductor comprising multiple shells may be terminated with all shells ending in the same plane or at different staggered planes as depicted in FIG. **20**.

[0228] In embodiments, the innermost conductor shell **2002** may be solid as shown in FIG. **20**. In embodiments the innermost conductor shell may be hollow defining a hole or cavity along its length along the z axis of the conductor.

[0229] In embodiments neighboring shells may be separated from each other by layers of an electrical insulator such that neighboring layers are not in electrical contact with one another. The thickness and material of the insulating layer may depend on the voltages, currents, and relative voltage potential between each neighboring shell. In general the insulator should be selected such that its breakdown voltage exceeds the voltage potential between neighboring conducting shells. In embodiments the outside of the outermost shell **2010** may be covered by additional electrical insulators or protective casing for electrical safety, durability, water resistance, and the like. In embodiments different shells and insulator layers may have different thicknesses depending on the application, frequency, power levels and the like.

[0230] Another view of a cross section of an embodiment of the conductor comprising four shells is shown in FIG. **21**. The figure shows a cross-section, normal to the z-axis, of the conductor comprising the conductor shells **2102**, **2104**, **2106**, **2108**. Note that in this figure, and in FIG. **20**, the insulating layers are not shown explicitly, but are understood to be located between the various shells. In embodiments, the thickness of the insulating layers may be extremely thin, especially in comparison to the thickness of the conducting shells.

[0231] The thickness, relative thickness, size, composition, shape, number, fraction of total current carried and the like, of concentric conducing shells may be selected or optimized for specific criteria such as the voltage and/or current levels carried by the wire, the operating frequency of the resonator, size, weight and flexibility requirements of the resonator, required Q-values, system efficiencies, costs and the like. The appropriate size, number, spacing, and the like of the conductors may be determined analytically, through simulation, by trial and error, and the like.

[0232] The benefits of the concentric shell design may be seen by comparing the current distributions in conductors of similar diameters but with different conductor arrangements. By way of example, calculations of the current distributions in two concentric shell conductor structures and one solid conductor are shown in FIGS. **22-24**. The figures show one

quarter of the cross section of the conductor with the conductor being symmetric around x=0, y=0 coordinate. The figures show the current density at 10 MHz for a copper conductor with an outside diameter (OD) of 1 mm and carrying a peak current of 1 A. Note that the darker shadings indicate higher current densities, as shown in the legend on the right hand side of the figure.

[0233] FIG. **22** shows the current distribution for a wire comprising a single, 1 mm diameter, solid core of copper. Note that the current is concentrated on the outer perimeter of the solid conductor, limiting the area over which the current is distributed, and yielding an effective resistance of 265.9 mΩ/m. This behavior is indicative of the known proximity effect.

[0234] FIG. **23** shows the current distribution for an embodiment where the 1 mm diameter wire comprises 24 mutually insulated 5.19 μm concentric conductive shells, around a solid innermost copper shell, totaling **25** conductive shell elements. Note that the optimal current density (i.e., the current distribution among the shells that minimizes the AC resistance, which may be found for any given structure using mathematical techniques familiar to those skilled in the art) in this structure is more uniformly distributed, increasing the cross section over which the current flows, and reducing the effective resistance of the wire to 55.2 mΩ/m. Note that this wire comprising concentric conducting shells has an AC resistance that is approximately five times lower than the similarly sized solid conducting wire.

[0235] FIG. **24** shows the current distribution for an embodiment where the 1 mm diameter wire comprises 25 conductive shells (including an innermost solid core) whose thicknesses are varied from shell to shell so as to minimize the overall resistance. Each shell is of a different thickness with thinner and thinner shells towards the outside of the wire. In this embodiment, the thickness of the shells ranged from 16.3 μm to 3.6 μm (except for the solid innermost shell). The inset in FIG. **24** shows the radial locations of the interfaces between the shells. The effective resistance of the wire comprising the varying thickness shells as shown in FIG. **24** is 51.6 mΩ/m. Note that the resistance of the conducting structures shown in FIGS. **22-24** was calculated analytically using methods described in A. Kurs, M. Kesler, and S. G. Johnson, Optimized design of a low-resistance electrical conductor for the multimegahertz range, Appl. Phys. Lett. 98, 172504 (2011), as well as U.S. Provisional Application Ser. No. 61/411,490, filed Nov. 9, 2010 the contents of each which are incorporated herein by reference in their entirety as if fully set forth herein. For simplicity, the insulating gap between the shells was taken to be negligibly small for each structure.

[0236] Note that while the embodiments modeled in FIGS. **23-24** comprised solid innermost conductor shells, most of the current flowing in that shell is confined to the outer layer of this innermost shell. In other embodiments, this solid innermost shell may be replaced by a hollow or insulator filled shell, a few skin-depths thick, without significantly increasing the AC resistance of the structure.

[0237] FIGS. **25-27** show plots that compare the ratio of the lowest AC resistance (as a function of the number of shells, N, and the operating frequency, f) achievable for a 1 mm OD wire comprising concentric conducting shells and a 1 mm OD solid core wire, of the same conducting material.

[0238] FIG. **25** shows that an optimized cylindrical shell conductor can significantly outperform a solid conductor of the same OD. One can also see from FIG. **25** that much of the relative improvement of an optimized concentric shell conductor over a solid conductor occurs for structures with only a small number of elements or shells. For example, a wire comprising 10 concentric conducting shells has an AC resistance that is three times lower than a similarly sized solid wire over the entire 2-20 MHz range. Equivalently, since the resistance of a solid conductor in the regime $\kappa D >> 1$ (κ being the inverse of the skin depth δ and D the diameter of the conductor) scales as 1/D, the conductor comprising ten shells would have the same resistance per unit length as a solid conductor with a diameter that is 3.33 times greater (and roughly 10 times the cross area) than the wire comprising shells.

[0239] Increasing the number of shells to **20** and **30** further reduces the AC resistance to four times lower, and five times lower than the AC resistance for a similarly sized solid wire.

[0240] It should be noted that with the presented structures comprising multiple conductor shells it may be necessary to impedance match each shell to ensure an optimal current distribution. However due to the relatively small number of shell conductors for most applications (<40) a brute force approach of individually matching the impedance of each shell (e.g., with a lumped-element matching network) to achieve the optimal current distribution could be implemented (similar impedance matching considerations arise in multi-layer high-T_c superconducting power cables (see H. Noji, Supercond. Sci. Technol. 10, 552 (1997). and S. Mukoyama, K. Miyoshi, H. Tsubouti, T. Yoshida, M. Mimura, N. Uno, M. Ikeda, H. Ishii, S. Honjo, and Y. Iwata, IEEE Trans. Appl. Supercond. 9, 1269 (1999). the contents of which are incorporated in their entirety as if fully set forth herein), albeit at much lower frequencies).

[0241] In embodiments, concentric conducting shells of a wire may preferably be cylindrical or have circular cross-sections, however other shapes are contemplated and may provide for substantial improvement over solid conductors. Concentric conducting shells having an elliptical, rectangular, triangular, or other irregular shapes are within the scope of this invention. The practicality and usefulness of each cross-section shape may depend on the application, manufacturing costs, and the like.

[0242] In this section of the disclosure we may have referred to the structures comprising multiple shells of conductors as a wire. It is to be understood that the term wire should not be limited to mean any specific or final form factor of the structures. In embodiments the structures may comprise free standing conductors that may be used to replace traditional wires. In embodiments the structures comprising multiple shells may be fabricated or etched onto a multilayer printed circuit board or substrate. The structures may be etched, deposited on wafers, boards, and the like. In embodiments thin concentric shells can be fabricated by a variety of processes (such as electroplating, electro-deposition, vapor deposition, or processes utilized in optical fiber fabrication).

[0243] The conductor structures may be utilized in many resonator or coil structures used for wireless energy transfer. The multi-shell structures may be used as part of a resonator such as those shown in FIG. **2**A-**2**E. The low loss conductors may be wrapped around a core of magnetic material to form low loss planar resonators. The low loss conductors may be etched or printed on a printed circuit board to form a printed coil and the like.

[0244] Source and Device Pairing for Wireless Energy Transfer

[0245] In exemplary embodiments, elements of a wireless energy transfer system may be paired to ensure that energy is being transferred between intended, authorized, and/or compatible system elements. System elements such as sources, devices, and repeaters may be separated from each other. In some configurations, multiple system elements may be in a position to transmit or receive power from one another. In some cases, only specific system elements may be designated, authorized, and/or compatible for energy transfer.

[0246] In exemplary embodiments, system elements may use an out-of-band communication channel to coordinate or adjust parameters of energy transfer. In many cases, the out-of-band communication channel may be decoupled or separate from the energy transfer channel. The out-of-band communication may use one or more components, frequencies, and/or protocols that are different from the energy transfer channel. In some instances, system elements may be "paired" to ensure that out-of-band communication channels and energy transfer channel are coupled or correspond to the same system elements.

[0247] In exemplary embodiments, signaling and communication may be performed using an in-band communication channel. Information may be transmitted using at least some components, fields, frequencies, and the like that are used for energy transfer. In-band communication may use substantially the same frequency spectrum, resonators, circuitry, and/or the like that are used for energy transfer. Communication using the in-band communication channel may occur while useful amounts of energy are being transmitted. In some cases, the energy transfer channel and the in-band communication channel may be considered the same channel. Information may be send using the energy transfer channel by modulating energy transfer, frequency of energy transfer, or other parameters.

[0248] In exemplary embodiments, system elements may be paired by exchanging or transmitting related information using an out-of-band communication channel and the in-band communication channel. In embodiments, system elements may be paired by exchanging or transmitting related information using an out-of-band communication channel and the energy transfer channel.

[0249] In exemplary embodiments, elements of an energy transfer system may be paired by first exchanging a first information using the in-band communication channel or energy transfer channel and later exchanging a second information using the out-of-band communication channel. The first information and the second information may preferably be deterministically related to one another. In some cases, the second information may be based on the first information. System elements may verify that the first and second information exchanged are related to one another to verify that the out-of-band communication channel corresponds to the in-band communication channel.

[0250] In exemplary embodiments, elements of an energy transfer system may be paired by first exchanging a first information using the out-of-band communication channel and later exchanging a second information using the in-band communication channel or energy transfer channel. The first information and the second information may preferably be deterministically related to one another. In some cases, the second information may be based on the first information. System elements may verify that the first and second information exchanged are related to one another to verify that the out-of-band communication channel corresponds to the in-band communication channel.

[0251] In some embodiments, elements of an energy transfer system may be paired by simultaneously exchanging a first information using the out-of-band communication channel and a second information using the in-band communication channel or energy transfer channel.

[0252] For example, system elements, such as a source and a device may be positioned within energy transfer distance. The source and device may include an out-of-band communication channel comprising Bluetooth communication modules. The source and device may also include an in-band communication channel. The in-band communication channel may transfer information using one or more energy transfer components. To initiate energy transfer, a source may energize one or more of its source resonators thereby generating an oscillating magnetic field in proximity of the source. The device may receive energy from the source via one or more device resonators. The source may transmit first information to the device by modulating the parameters of the energy transfer channel. The device may receive the first information by detecting changes in the energy transfer channel. The first information may include a Bluetooth pairing code for the source Bluetooth communication module and/or other unique code. The device may initiate out-of-band communication and send a second information to the source via the out-of-band communication channel. The second information may include the unique Bluetooth pairing code. The source may receive the second information via the out-of-band communication channel and confirm that it matches the first information sent via the in-band communications channel. If the first and second information match the energy transfer channel and the out-of band communication channel may be verified to be related or associated with the same system elements and the source and device may be considered "paired".

[0253] In another example, system elements, the source and device may include an out-of-band communication channel comprising Bluetooth communication modules and an in-band communication channel. To initiate energy transfer a source may energize one or more of its source resonators thereby generating an oscillating magnetic field in proximity of the source. The source may transmit first information to the device by modulating the parameters of the energy transfer channel. The source may also initiate out-of-band communication and send or broadcast a second information via the out-of-band communication channel. The second information may preferably be related to the first information. A device may receive the second information via the out-of-band communication channel and the first information via the in-band communication channel. The device may determine if the first information matches or is related to the second information. If the first and second information match or are related the energy transfer channel and the out-of band communication channel may be verified to be associated with the same system elements and the source and device may be considered paired.

[0254] Exchange of the first information and the second information may be initiated by any one of the system elements. The first information may be transmitted from the device to the source. The device may module the impedance of one or more of its device resonators. The change in impedance may affect the reflected impedance in a source resonator

of the source which may affect the currents or voltages on the source resonator. The second information may also be transmitted from the device to the source. A device may broadcast or transmit second information via an out-of-band communication channel.

[0255] The first information and the second information may be messages, data packets, binary signals, analog modulations, or other signals that may be used to convey information. The first information and/or the second information may include unique pairing codes, cryptographic tokens, specific communication parameters, and the like. In some cases, the first information and the second information may include one or more sequential or concurrent messages or signals. The first information may include a Public Universal Unique Identifier (PUUID). A PUUID may be a 48 bits long identifier and may be unique to the chip on a particular wireless power source. In embodiments, the PUUID can be compressed or "hashed" to 16 bits so it takes less energy and/or time to transmit the signal.

[0256] In some embodiments the first information transmitted over an in-band communication channel may include source power waveform synchronization. Source power waveform synchronization may be a modulation of the magnetic field used for energy transfer. The modulation may causes voltage and/or current modulations on device resonators. The modulations may be configured to change in a specific pattern. The second information, transmitted using an out-of-band communication channel, may include unique points or descriptors of the modulations produced by the source. A device, having both the second information that includes out-of-band waveform points or descriptors and the first information that includes measured in-band voltage and/or current changes, may determine whether the two match. If the first information and the second information correspond to the same system element, the second information should include data that describes the waveforms or modulations observed in the in-band communication channel. A device may verify if the second information accurately describes the modulations (first information) in the in-band communication channel. If the first information and the second information match the energy in-band communication (energy transfer) channel and the out-of-band communication channel may be paired and assumed to correspond to the same system element.

[0257] In embodiments, source power waveforms may synchronize or otherwise be differentiated using time, frequency, phase, amplitude, or other unique characteristics of a particular waveform. A source power waveform may include a specific periodic shape or characteristic. A pattern may include specific timing of amplitude changes, specific rise/fall times.

[0258] FIG. **28** shows one example of a power synchronization sawtooth waveform with uniquely identifiable features. The sawtooth waveform may be characterized using the period length (Tp) and its rise time (Tr). The waveform may be modulated onto the oscillating magnetic fields used for energy transfer. In some embodiments, the power output of a source may be modulated according to the shape of the waveform. The magnitude of the oscillating magnetic fields used for energy transfer may change in accordance to the waveform. The highpoints of the waveform may correspond to high power output and the low points of the waveform may correspond to the low power output. Changes in the output power of the source may be detectable by the device as input power changes.

[0259] In some embodiments, the frequency of the magnetic fields generated by the source may be modulated according to the waveform. The highpoints of the waveform may correspond to higher frequencies of magnetic fields and the low points of the waveform may correspond to the lower frequencies of the magnetic field generated by a source. Changes in the frequencies may be detectable by the device as changes in input frequencies or change in power input.

[0260] In some embodiments, the frequency of the magnetic fields generated by the source may be modulated according to the waveform. The highpoints of the waveform may correspond to higher frequencies of magnetic fields and the low points of the waveform may correspond to the lower frequencies of the magnetic field generated by a source. Changes in the frequencies may be detectable by the device as changes in input frequencies or change in power input.

[0261] In another embodiment, the impedance of a source resonator may be modulated according to the waveform. The highpoints of the waveform may correspond to higher impedance of the source resonator used for energy transfer and the low points of the waveform may correspond to the lower impedance of the source resonator. Changes in the source impedance may be detected at a device. Change in impedance may of the source may manifest as changes in impedance, voltage, power, current of a device resonator. Likewise, the impedance of a device resonator may be modulated according to the waveform. Changes in the device impedance may be detected at a source. Change in impedance may of the device may manifest as changes in impedance, voltage, power, current of a source resonator.

[0262] In embodiments, the signal modulation depth on the magnetic field may be 1% of the signal power. In embodiments, the modulation depth may be 5%, 10% or 50% of the signal. In embodiments, modulation depth may be related to the modulation frequency. In embodiments, the modulation of the magnetic field may be a phase modulation or may be a frequency modulation. In embodiments, any known carrier modulation schemes may be used to modulate the magnetic field generated by the wireless power source.

[0263] A sawtooth waveform, such as the one shown in FIG. **28**, for example, provides easily identifiable characteristics. The ramp rate and/or amplitude of the waveform may be unique and easily determined using simple hardware/software. The sharp edge of the sawtooth waveform may provide an easily identifiable feature which can be used by to accurately determine relative time, frequency, and phase of the waveform. A system element, such as a device may be configured to monitor a received power signal and determine the timing of specific transition points or unique features. A device may be configured, for example, to identify transition points in the waveform. The transitions points **2802**, **2804**, **2806**, may include points in the waveform that mark a start of a rise in waveform, the start of a fall in the waveform and the like. Using three or more points of the waveform, a device may determine the Tp and Tr values of the waveform.

[0264] The timing, the absolute maximum the relative values of magnitude of waveform points, and other characteristics may be used to identify or characterize waveforms. Waveforms may include square waveforms, triangular waveforms, and any number of other waveform shapes and easily identifiable features. Waveforms and waveform characteristics may be specifically designed to minimize needed communication bandwidth, increase robustness in certain environmental conditions, decrease time required for synchronization, ensure

compliance with codes or regulations, be more easily identifiable or other requirements dependent on system architecture or environment.

[0265] For example, FIGS. **29**A and **29**B depict some additional examples of waveform characteristics that may be used for pairing. The waveforms may include multilevel modulations, such as that shown in FIG. **29**A in which the modulation level at **2902** is greater than **2902**. The waveforms may even include arbitrarily shaped waveforms, such as waveform shapes **2908**, **2910**, and **2912** as shown in FIG. **29**B, and thus may require four or more points for characterization.

[0266] The system element transmitting the waveform can also broadcast or transmit the identifying waveform characteristics using an out-of-band communication channel. A different system element may monitor the waveform and compare the measured waveform characteristics to the characteristics defined by the information in the out-of-band communication channel. If the two match then the energy transfer channel or the in-band communication channel may be associated with the out-of-band communication channel and the source and device may be considered paired.

[0267] In one embodiment, different system may be programmed with different waveform parameters. In the case of the example sawtooth waveform, different system elements may be preprogrammed with unique Tr and Tp values and configured to generate a waveform consistent with the preprogrammed values.

[0268] In some embodiments, system elements, using an out-of-band communication channel may collaborate and identify waveform patterns and characteristics that may be unique to each element and unique enough to be identifiable and distinguishable from one another. In some cases system elements may include two or ten or even twenty or more preprogrammed waveform parameters. One of the waveform parameters may be selected for each system element. System elements may communicate or broadcast their waveform parameters using the out-of-band communication channel to other system elements. When the same or similar waveform parameters are detected the system elements may coordinate to resolve the parameter overlap.

[0269] In some embodiments, system elements may randomly or deterministically select waveform parameters. The system elements may then monitor the in-band (energy transfer) channel. System elements may monitor to determine if another system element is transmitting a waveform with the same or similar waveform parameters. If another system element is determined to be using similar or the same waveform parameters the system element may select another waveform pattern or use the out-of-band communication channel to resolve the waveform parameter overlap.

[0270] In exemplary embodiments, system elements may transmit the first information and the second information periodically. For example, a source may periodically module the power transfer parameters to transmit the first information and periodically transmit the second information via the out-of-band communication channel. In some cases, system elements may transmit the first and/or the second information in response to a request from another system element. In some cases, system elements may transmit the first and/or the second information in response to a system change such as a new system element coming in proximity to leaving the proximity or another system element.

[0271] In another embodiment, system elements, such as sources can time schedule to ensure only one source is actively providing a synchronization waveform. One such exemplary method of time scheduling is round-robin scheduling. Another exemplary method of time scheduling is priority scheduling.

[0272] FIG. **30** depicts a block diagram of a system element **3202** configured for pairing. The system element may include one or more resonators **3204**. The resonator **3204** may be configured for transmitting or receiving energy. The resonator **3204** may also receive the first information via the magnetic fields used for energy transfer. Changes or modulations in the magnetic field, impedance of external resonators, and the like may be detected by characteristic sensors **3206**. The sensors **3206** may include voltage, current, frequency, or other sensors for monitoring electrical parameters on the resonator. The sensors may include analog and/or digital electronics. Comparators, amplifiers, and the like may be used to detect voltage or current thresholds. In some embodiments, analog to digital converters may be used to sample voltages and currents on the resonator. Second information that may include waveform characteristics may be received on an out-of-band communication channel **3210**. The waveform characteristics of the second information may be stored in waveform table **3212** in the element **3202**. An analysis module **3208** may use the waveform characteristics and analyze the captured first information to determine if the waveform characteristics match the modulations captured by the resonator.

[0273] FIG. **31** depicts an embodiment of a method for pairing two or more system elements using a signal or a waveform. The method may be performed by a system element, such as a wireless power source. In step **3102**, system elements may be identified. System elements such as sources, devices, repeaters, and the like may identify their presence using an out-of-band communication signal. System elements may send a broadcast signal use one or more discovery protocols for identifying other system elements that may be in proximity. In step **3104**, a system element may transmit second information using the out-of-band communication channel. The second information may be sent directly to the identified system elements. In some cases, the second information may be broadcast regardless if any system elements were identified. The second information may include waveform characteristics. The waveform characteristics may include timing information, relative levels, and other characteristics for uniquely describing a waveform. The waveform characteristics may be selected from a set of predefined waveform characteristics. In some cases, the system element may be assigned a unique waveform characteristic. In some embodiments, the waveform characteristic may be dynamically determined.

[0274] In step **3106**, the system element may transmit a waveform that matches the waveform characteristics using an in-band communication channel. The in-band communication channel may modulate one or more parameters of the fields or components used for energy transfer. A second system element may receive both the waveform and the waveform characteristics and determine if the waveform matched the waveform characteristics sent using the in-band communication channel (step **3108**). In step **3110**, if the waveform matches the waveform characteristics the second system element may pair the in-band and out-of-band communications channels and pair to the system element.

[0275] FIG. **32** depicts an exemplary embodiment of a method for pairing two or more system elements using a signal, such as a waveform. The method may be performed by

a system element, such as a source or a device. In step **3202**, a system element may transmit a first signal using an in-band communication channel. In embodiments, the first signal may be unique to that system element. The in-band communication channel may be part of the energy transfer channel. The first signal may be received when energy is being received by the system element. The characteristics of energy transfer may be modulated to transmit the signal. In step **3204**, the system element may receive first signal characteristics using an out-of-band communication channel. In embodiments, the signal characteristics may include a description of a signal, a set of steps of identifying a signal, or other descriptors. In step **3206**, the system element may analyze the received signal and identify characteristics of the signal. Voltage, current, frequency, impedance, and other readings on the resonator of the system element may be analyzed to determine patterns or unique points or changes in the signal. In some cases, the readings may be sampled and saved. In step **3208**, the identified characteristics of the signal and the characteristics received via the out-of-band communication channel may be compared to determine if they are the same or similar. If the characteristics do not match, the system element may receive additional signal characteristics using the out-of-band communication channel from other system elements to find a matching out-of-band communication channel in step **3212**. If the characteristics match, in step **3210** the in-band communication channel (energy transfer channel) may be paired or associated with the out-of-band communication channel. The out-of-band communication channel may be used to signal commands or power control messages to the paired system element. In some cases, after a period of time or due to events in the system, the process may be repeated to repair the communication channels and the system elements.

[0276] In exemplary embodiments, pairing may be established between a source and a device such that a device may send power control messages to the source via the out-of-band communication channel. In response to the messages, the source may adjust the parameters of the energy transfer or the energy transfer channel. In some cases, more than one device may be paired to a source. More than one device may send power control messages to a source. In such configurations, the source may prioritize the devices. In cases where power control messages from two or more devices conflict or may not be simultaneously satisfied, only power control messages from the highest priority device may be accepted and others ignored. Devices may be ranked or prioritized based on the power demands, order of pairing, type of device, coupling strength, and the like. For example, a source may prioritize a device that has a higher power demand, a first device that paired with the source before a second device, or a device with which the source has the greatest coupling. In some cases, a source may transmit power control signal or messages to one or more devices. The power control messages sent from a source to a device may instruct a device to detune itself so that it receives less power than a higher priority device.

[0277] In exemplary embodiments, system elements such as sources may have different operating parameters depending if the element is paired or not. In the case of an energy source, for example, the source may operate in a low power mode until successful pairing. A successful pairing may enable the source to transmit higher energy levels.

[0278] In exemplary embodiments, the in-band communication channel may be used to transmit arbitrary messages. The magnetic field used to transfer energy may transfer a modulated signal between system elements. The modulated signal may be a code signal, a key signal, an identifier signal, an authentication signal, and/or the like. System elements may detect modulated signal and receive and decode that modulated signal. To pair to second system element a first system element may receive a first message on the in-band communication channel and send a replica or altered version of the first message back via an out-of band communication channel to the second system element such as a Bluetooth signal. When the second system element receives the modulated signal from the first system element, it can compare it to the modulated signal it generated. If the receive signal matches or correlates with the transmitted signal first and second elements may be within an energy transfer distance and may be paired. FIG. **33** shows a plot of an example of signaling by a wireless power source. Starting at time t=0, the source may emit a first signal with a certain magnitude for 30 milliseconds. This signal may be emitted every 250 milliseconds. When a current change is detected, such as when a device approaches and/or couples to the source, the source may output a second signal with a larger magnitude after approximately 10 milliseconds. This second signal may have a duration of 750 msec. This second signal may be modulated "in-band" to transmit a frame of symbols used to connect with a device. The device may transmit back to the source the frame symbols or part of the frame symbols using an out-of-band communication channel to pair the source and device.

In-Band Communication with Impedance Modulation

[0279] In some embodiments, bi-directional communication between system elements may be used to regulate power, transmit information, increase efficiency, prioritize, energy delivery, coordinate energy delivery, and the like. In some embodiments, bi-directional communication between system elements maybe based on in-band communication.

[0280] Modulations of the current and/or voltage of source resonators, for example, may cause a modulated power output on coupled device resonators. Changes in power output in a coupled device may be measured and decoded into messages. In another example, modulations the impedance of device resonators may cause changes in the reflected impedance in coupled source resonators. A change in device impedance may cause a change in the reflected impedance in the source. Changes in impedance may be monitored in the source resonator. Changes in impedance may manifest themselves as changes in power in the source resonator. Changes in impedance of one or more devices may cause changes or modulation in the voltages, currents, and/or frequency of resonators in the source. In some embodiments, changes or modulations of the impedance of one device may cause changes or modulations in reflected impedance in other devices that are coupled to the same source. The changes in impedance may be used to transmit information from devices to a source and/or between devices.

[0281] In embodiments, a resonant multi-device in-band communication system may use the effect of reflected power modulation to communicate between all devices and sources in a coupled configuration. Reflected power modulation is the effect that occurs when any number of devices uses resonant coupling impedance modulation to cause the source magnetic field to modulate in-turn. The modulation of the source magnetic field may cause a power modulation seen by all coupled devices.

[0282] For example, FIG. **34** shows a representation of one configuration of wireless energy transfer system comprising one source **3408** with one or more source resonators and three devices **3402**, **3404**, **3406**, each with one or more device resonators. Each of the devices may be coupled to the source and receive energy. In-band communication may be used between the source and the devices to coordinate and control the energy transfer.

[0283] The source **3408** may transmit information to the devices by modulating the power transfer characteristics. The source may, for example modulate the voltage/current at the source resonator. The changes in current/voltage may result in changes in power output of the source. The changes in the current/voltage at the source resonator may be induced by altering the parameters or output of the amplifier driving the source resonator. In some cases the power output of the source may be modulated by changing the impedance, resonant frequency, or resistance of the resonator. Changing the resonant frequency, for example, may change the power delivered to the source resonator from the amplifier driving the source resonator. Impedance, frequency, and/or resistance of a resonator may be modulated with variable components such as capacitors, inductors, and/or resistors that may be connected to the source resonator.

[0284] A device **3402**, **3404**, **3406** that is coupled to the source **3408** may see manifestations of the modulations at the source with modulations or changes in voltage and/or current at the device resonator of the device. A device may include sensing circuitry such as analog to digital converts, differential amplifiers, and other circuitry for measuring or detecting modulations in the current/voltages of the resonator.

[0285] A device **3402**, **3404** or **3406** may transmit information to the source by modulating the impedance of one or more of the device resonators coupled to a source resonator of the source **3408**. The device may, for example modulate the impedance of a device resonator. Changing the impedance of a device resonator coupled to a source may change the reflected impedance seen by the source resonator. The changes or modulation in the impedance of the source resonator may manifest as changes and modulations in current or voltage on the source resonator. The source may monitor the voltage and/or current to identify modulations and determine if data has been transmitted from one of the devices.

[0286] A device **3402**, **3404** or **3406** may transmit information to another device that is coupled to the same source by modulating the impedance of one or more of the device resonators coupled to a source resonator of the source **3408**. The device may, for example, modulate the impedance of a device resonator. Changing the impedance of a device resonator coupled to a source may change the reflected impedance seen by the source resonator. The changes or modulation in the impedance of the source resonator may manifest as changes and modulation in current or voltage on the source resonator. The change in impedance at the source resonator may also result in changes or modulation of the power output of the source. The changes or modulation in the power output may correspond to the modulations of device impedance. The modulations of the power output of the source may be detected and monitored by other devices coupled to the source thereby allowing a device to communicate in-band with other devices coupled to the same source.

[0287] In embodiments during in-band communication from a device to another device via the source, a source may amplify the modulations generated by the device. Induced modulations on a source resonator caused by a impedance modulations of a device resonator may be monitored by the source and regenerated by the source by modulating the power output of the source.

[0288] The device may modulate the impedance of one or more of its device resonators by adjusting the values of one or more of capacitance, inductance, or resistance that may be connected to the device resonator. FIG. **35** depicts a simplified device **3502** with in-band communication capability. The device **3502** includes a device resonator coil **3504** and an impedance matching network **3506**. The device **3502** further includes one or more additional elements **3508**, **3510**, **3512**. The elements may be capacitors, inductors, resistors, and the like.

[0289] The elements may be selectively coupled into the circuit with a switches **3514**, **3516**, **3518** in series with the elements. The switches may be selectively activated to connect one or more of the elements **3508**, **3510**, **3512** to the resonator coil. The activation of a switch may change the impedance of the resonator of the device according to the value of the element that is connected via the switch. In embodiments, a device may modulate the impedance of its device resonator by modulating or activating the switches connected to the elements **3508**, **3510**, **3512**.

[0290] In embodiments, the values of the elements **3508**, **3510**, **3512** may be different, allowing a multilevel modulation of the impedance. In some cases three or more levels may be possible. In embodiments, a device may be independently capable of modulating its impedance at multiple levels and multiple frequencies. The devices may also be independently capable of measuring input voltage, current, or both. In some embodiments, multi-level impedance modulation may be used to allow for many bits per symbol in a communication scheme.

[0291] In some embodiments, multi-level impedance modulation may be used to compensate for differences in coupling between devices and source. To provide a reliable modulation that may be detectable for different coupling strengths between source and device resonators, the magnitude of modulations on a device may be based, at least in part, on the coupling strengths. In the case where a device and a source have relatively high coupling (i.e. they are in close proximity) the magnitude of impedance modulations may be relatively smaller compared to when a device and a source have low coupling (i.e. they are separated by a distance equal to their sizes). During low coupling, the impedance of a device resonator may be modulated with large element values. During high coupling, the impedance of the device resonator may be modulated with small element values.

[0292] In some embodiments, a communication scheme may use known or communicated impedance modulation levels to infer associated device coupling. In some cases the coupling between a source and a device may be determined by predefined impedance modulations. A device may be configured to periodically or in response to an event modulate the impedance of its device resonator. The modulations may be based on a predefined pattern with predefined changes in magnitude. Based on the changes in the reflected impedance of a coupled source the source may determine the coupling strength and may communicate that to the device. In some cases a source may use predefined modulation sequence that may be detected by the devices allowing the devices to identify the coupling strength to the source. In some cases, auto-

matic gain control circuits can be used for measuring the voltage and/or current across the load to ensure enough Signal to Noise Ratio (SNR).

[0293] In some embodiments, a communication scheme may use time, frequency, code, or other methods of multiplexing in-band communication from multiple devices. In some embodiments, a communication scheme may use fixed reflected impedance on source (i.e. may require devices to modulate at an independent impedance level based on coupling) to determine number of devices attempting to communicate simultaneously.

[0294] As an example, using encoding methods such as biphase encoding, each device can cause a reflected power modulation at various levels and frequencies on the source resonator. The reflected power modulation levels and frequencies on the source resonator may be used by the source and other paired devices to communicate necessary information about the wireless system or data otherwise useful to the source and/or paired devices. The wireless resonant system does not interfere with neighboring wireless resonant systems due to the near-field nature of reflected power modulation.

[0295] In some embodiments, impedance modulation on a device may involve the same components that may be used for tuning of the device resonator.

[0296] In some embodiments, a communication scheme may use the concept of device multi-frequency impedance modulation whereby devices modulate impedance at different frequency levels. A new device can listen to all other devices and determine an available frequency slot and even number of other devices for its communication. Other multiplexing methods can use similar concept.

[0297] In some embodiments, in source resonant circuits that enforce constant current in the source resonator (i.e. LCL like topologies), the reflected power modulation can be active whereby the source listens to all devices and then actively modulates its own source resonator current when it determines necessary to pass along information to other devices.

[0298] In some embodiments, a device may use physical changes of the resonator to induce reflected impedance or self-impedance changes on the source.

[0299] FIG. **36** depicts one embodiment of a method for establishing and using an in-band communication channel based on impedance modulation. In step **3602**, the device may receive a predetermined signal modulation pattern. The pattern may be a multilevel modulation pattern with predefined levels of modulation. The predefined pattern may be generated by a source. The source may modulate the impedance of the source resonator. Changes in source impedance may manifest as changes in current/voltage at a coupled device resonator. In step **3604**, the modulations of the voltages/currents on the device resonator may be measured and the relative and absolute magnitude of the modulations may identified. Based on the observed modulation levels the device may determine the coupling factor between the device resonator and the source resonator in step **3606**. Based on the identified coupling factor, the necessary modulation levels for communicating with the source or other devices may be established in step **3608**. In step **3610**, the device may modulate the impedance of a device resonator according to the determined levels to transmit data to the source or other devices. The in-band communication exchange may be used coordinate energy transfer or communicate energy transfer adjustments in the system.

[0300] While the invention has been described in connection with certain preferred embodiments, other embodiments will be understood by one of ordinary skill in the art and are intended to fall within the scope of this disclosure, which is to be interpreted in the broadest sense allowable by law.

[0301] All documents referenced herein are hereby incorporated by reference in their entirety as if fully set forth herein.

What is claimed is:

1. A method comprising:

transmitting, by a wireless power source, a signal with a first characteristic via an in-band communication channel;

receiving via an out-of band communication channel, by the wireless power source, information from a first wireless power device; and

determining, by the wireless power source, if the information includes the first characteristic.

2. The method of claim **1** further comprising transferring wireless power between the wireless power source and the first wireless power device if the information includes the first characteristic.

3. The method of claim **1** further comprising receiving second information via the out-of-band communication channel if the information does not include the first characteristic; and determining, by the wireless power source, if the second information includes the first characteristic.

4. The method of claim **1** wherein the signal is a power transfer signal with a frequency approximately equal to a resonant frequency of the wireless power source.

5. The method of claim **1** wherein the signal is a modulated power transfer signal having a frequency and an amplitude.

6. The method of claim **5** wherein the modulated power transfer signal contains an identification code unique to the wireless power source.

7. The method of claim **1** further comprising:

receiving via the out-of-band communication channel by the wireless power source, a second information from a second wireless power device;

determining, by the wireless power source, if the second information includes the first characteristic; and

transferring wireless power between the wireless power source and the second power device if the second information includes the signal.

8. The method of claim **7** further comprising prioritizing wireless power transfer to the first and second wireless power devices.

9. The method of claim **8** wherein the priority is based on power demands of the first and second wireless power devices, order of pairing with one of the first and second power devices, type of device, or strength of coupling between the wireless power source and each of the first and second wireless power devices.

10. The method of claim **8** further comprising transmitting a power control signal to one of the first and second wireless power devices that has a lower priority to detune itself.

11. A method comprising:

receiving, by a wireless power device, a predetermined signal modulation from a wireless power source;

determining, by the wireless power device, modulation parameters based on the predetermined signal modulation;

determining, by the wireless power device, a coupling factor between the wireless power source and the wireless power device based the modulation parameters;

modulating, by the wireless power device, an impedance of the wireless power device based on the coupling factor.

12. The method of claim **11** further comprising monitoring the modulation of the impedance of the wireless power device at the wireless power source.

13. The method of claim **12** further comprising changing, by the wireless power source, power output in response to the modulated impedance of the wireless power device.

14. The method of claim **11** further comprising transmitting information from the wireless power device to the wireless power source using the modulated impedance.

15. The method of claim **11** wherein the impedance is the impedance of a device resonator of the wireless power device.

16. The method of claim **11** further comprising modulating the impedance of the wireless power device at one or more amplitudes and at one or more frequencies.

17. The method of claim **11** wherein the impedance is the impedance of the load of the wireless power device.

18. The method of claim **11** further comprising monitoring for an impedance modulation of another wireless power device in the vicinity of the wireless power device.

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