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(54) **Titre : SYSTEME DE TRANSMISSION DE PUISSANCE DE CHAMP ELECTRIQUE SANS FIL, EMETTEUR ET RECEPTEUR POUR CE DERNIER ET PROCEDE DE TRANSFERT SANS FIL DE PUISSANCE**

(54) **Title: WIRELESS ELECTRIC FIELD POWER TRANSMISSION SYSTEM, TRANSMITTER AND RECEIVER THEREFOR AND METHOD OF WIRELESSLY TRANSFERRING POWER**

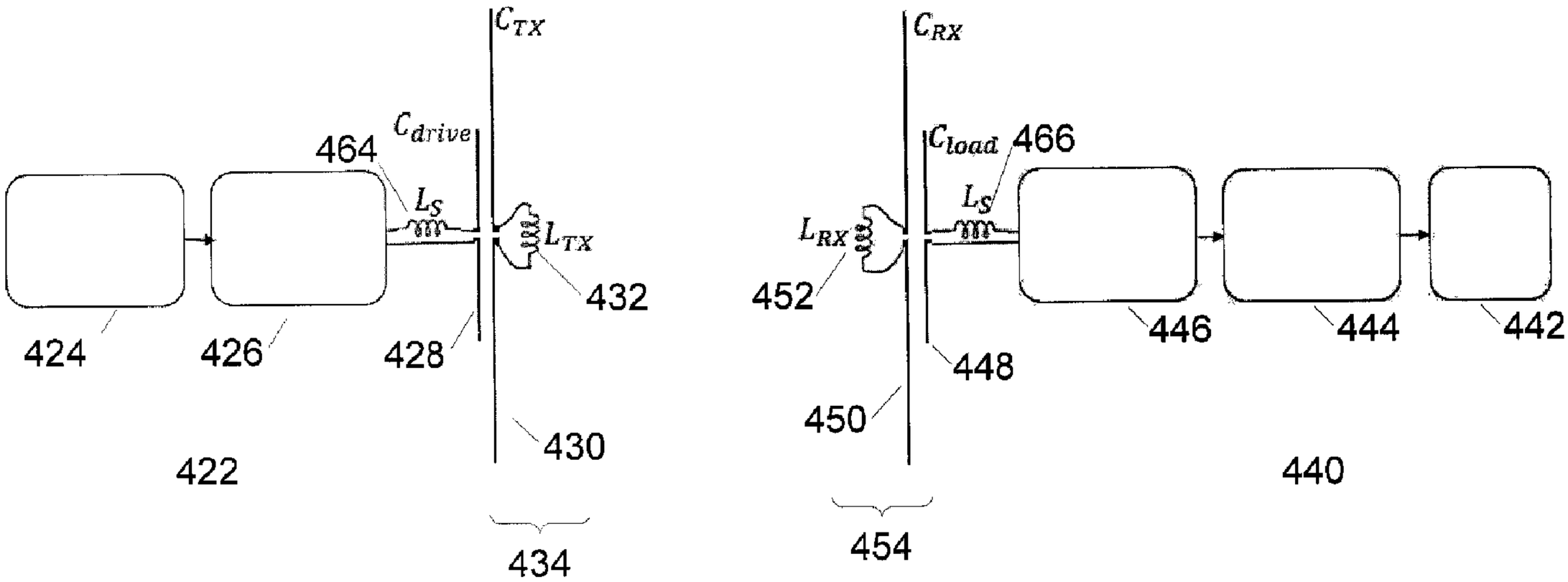



Figure 15

(57) **Abrégé/Abstract:**
A wireless electric field power transmission system comprises a transmitter comprising a transmit resonator and a transmit capacitive balun, and at least one receiver comprising a receive resonator and a receive capacitive balun. The transmit capacitive balun is configured to transfer power to the transmitter resonator, the transmit resonator is configured to transfer the power to the receive resonator, and the receive resonator is configured to extract the power to the receive capacitive balun via electric field coupling.

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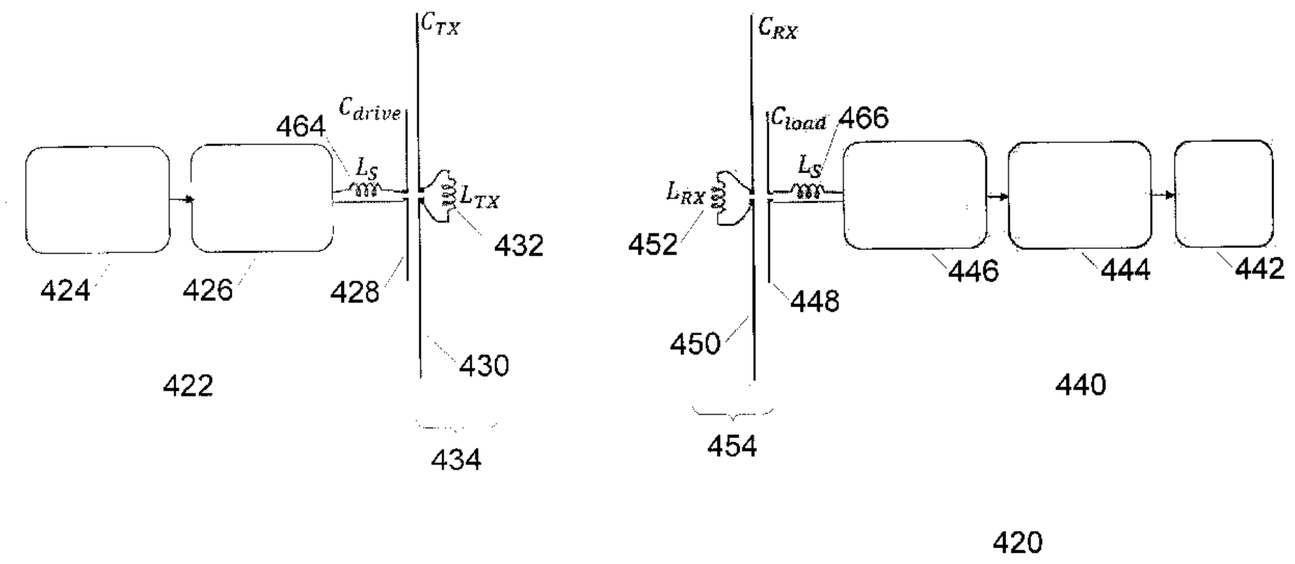



Figure 15

**(57) Abstract**: A wireless electric field power transmission system comprises a transmitter comprising a transmit resonator and a transmit capacitive balun, and at least one receiver comprising a receive resonator and a receive capacitive balun. The transmit capacitive balun is configured to transfer power to the transmitter resonator, the transmit resonator is configured to transfer the power to the receive resonator, and the receive resonator is configured to extract the power to the receive capacitive balun via electric field coupling.

WO 2015/196302 A1

# WIRELESS ELECTRIC FIELD POWER TRANSMISSION SYSTEM, TRANSMITTER AND RECEIVER THEREFOR AND METHOD OF WIRELESSLY TRANSFERRING POWER

## Field

**[0001]** The subject application relates generally to wireless power transmission and in particular, to a wireless electric field power transmission system, a transmitter and receiver therefor and a method of wirelessly transferring power.

## Background

**[0002]** A variety of radiative or far-field, and non-radiative or near-field, energy or power transfer techniques are known. For example, radiative wireless information transfer using low-directionality antennas, such as those used in radio and cellular communications systems and home computer networks, may be considered wireless energy transfer. As will be appreciated, this type of radiative energy transfer is inefficient because only a small portion of the supplied or radiated power, namely, that portion in the direction of, and overlapping with, the receiver is picked up. The vast majority of the power is radiated in other directions and lost in free space. Such inefficient energy transfer may be acceptable for data transmission, but is not practical when trying to transfer useful amounts of electrical energy for the purpose of doing work, such as for example, powering or charging electrical or electronic devices. One way to improve the transfer efficiency of some radiative energy transfer schemes is to use directional antennas to confine and preferentially direct a beam of radiated energy towards a receiver. However, these directed radiation schemes typically require an uninterruptible line-of-sight between the transmitter and receiver as well as potentially complicated tracking and steering mechanisms in the case of mobile transmitters and/or receivers. In addition, such directed radiation schemes may pose hazards to objects or people that cross or intersect the beam of radiated energy when modest to high power beams of energy are being transmitted.

**[0003]** A known non-radiative, or near-field, wireless power transmission system, often referred to as either induction or traditional induction, does not (intentionally) radiate power, but instead uses an alternating current passing through a primary coil, to generate an alternating magnetic near-field that induces currents in a near-by receiving or secondary coil. Induction schemes of this nature have demonstrated the

ability to transmit modest to large amounts of power, however only over very short distances, and with very small offset tolerances between the primary coil and the secondary coil. Electric transformers and proximity chargers are examples of devices that utilize this known short range, near-field energy transfer scheme.

**[0004]** PCT Application Publication No. WO 2009/089146 discloses a wireless power transmission system that includes a transmitter and a receiver. The transmitter includes a radio frequency energy generator, a first transmitting plate, and a second transmitting plate. The first transmitting plate is operatively coupled to the radio frequency energy generator. The second transmitting plate is operatively coupled to ground. The receiver includes a rectifier, a first receiving plate, and a second receiving plate. The first receiving plate is operatively coupled to the rectifier. The first receiving plate is configured to be capacitively coupled to the first transmitting plate and the second receiving plate is configured to be capacitively coupled to the second transmitting plate. The second receiving plate is operatively coupled to ground.

**[0005]** U.S. Patent Application Publication No. 20110198939 discloses a transmitter that includes a substantially two-dimensional high-Q resonator structure including a flat coil and an impedance-matching structure operably connected to the resonator structure. The transmitter is configured to transmit power wirelessly to another high-Q resonator.

**[0006]** U.S. Patent Application Publication No. 20090206675 discloses means for transporting electrical energy and/or information from a distance by using, at a slowly varying regime, the Coulomb field which surrounds any set of charged conductors. A device is composed of energy production and consumption devices situated a short distance apart, and it uses neither the propagation of electromagnetic waves nor induction and cannot be reduced to a simple arrangement of electrical capacitors. The device is modeled in the form of an interaction between oscillating asymmetric electric dipoles, consisting of a high-frequency high-voltage generator or of a high-frequency high-voltage load placed between two electrodes. The dipoles exert a mutual influence on one another. The device is suitable for powering industrial and domestic electrical apparatus and is especially suitable for powering low-power devices moving in an environment and for short-distance non-radiating transmission of information.

**[0007]** Although wireless power transmission techniques are known, improvements are desired. It is therefore an object to provide a novel wireless electric field power transmission system, a transmitter and receiver therefor and a method of wirelessly transmitting power.

## Summary

**[0008]** Accordingly, in one aspect there is provided a wireless electric field power transmission system comprising: a transmitter comprising a transmit resonator and a transmit capacitive balun; and at least one receiver comprising a receive resonator and a receive capacitive balun, wherein, via electric field coupling: the transmit capacitive balun is configured to transfer power to the transmit resonator, in response, the transmit resonator is configured to transfer power to the receive resonator, and the receive capacitive balun is configured to extract power from the receive resonator.

**[0009]** According to another aspect there is provided a method of wirelessly transferring power, the method comprising: delivering power from a source to a transmit resonator via a transmit capacitive balun via electric field coupling; in response, transferring power from the transmit resonator to a receive resonator via electric field coupling; and extracting power from the receive resonator via a receive capacitive balun via electric field coupling.

**[0010]** According to another aspect there is provided a transmitter for wirelessly transferring power, the transmitter comprising: a capacitive balun configured to receive an alternating signal and in response generate an electric field; and a transmit resonator, responsive to the electric field generated by the capacitive balun, configured to resonate and generate an electric field to a receiver.

**[0011]** The transmit resonator may, responsive to the electric field generated by the capacitive balun, be configured to resonate and generate a resonant electric field to the receiver. The capacitive balun and the transmit resonator may, responsive to the electric field generated by the capacitive balun, be configured to resonate and generate a resonant electric field to the receiver. The capacitive balun may be configured to receive the alternating signal and in response generate a resonant electric field. The transmit resonator may, responsive to the resonant electric field generated by the capacitive balun, be configured to resonate and generate the

electric field to the receiver. The transmit resonator may, responsive to the resonant electric field generated by the capacitive balun, be configured to resonate and generate a resonant electric field to the receiver.

**[0012]** The transmit resonator may comprise laterally spaced electrodes interconnected by a series inductor and the capacitive balun may comprise laterally spaced conductive elements, each conductive element being proximate to and spaced from at least one respective electrode. The conductive elements and electrodes may be in substantial alignment so that major faces of the conductive elements and electrodes face one another. The conductive elements and electrodes may also be generally planar and may have substantially similar dimensions. Alternatively, the conductive elements and electrodes may be of different dimensions and may be curved, angled and/or textured.

**[0013]** The transmitter may also further comprise a power inverter connected across the capacitive balun, the power inverter configured to output the alternating signal that excites the capacitive balun.

**[0014]** The transmitter may also further comprise a source configured to generate the alternating signal that excites the capacitive balun.

**[0015]** The alternating signal may be a radiofrequency (RF) signal.

**[0016]** According to another aspect, there is provided a receiver for wirelessly receiving power, the receiver comprising: a receive resonator configured to resonate in the presence of a generated electric field; and a capacitive balun capacitively coupled to the receive resonator and configured to output an alternating signal in response to resonance of the receive resonator.

**[0017]** The receive resonator may be configured to resonate in the presence of a generated resonant electric field. The receive resonator may, responsive to the generated resonant electric field, be configured to resonate and generate a resonant electric field. The receive resonator and the capacitive balun may, responsive to the resonant electric field generated by the receive resonator, be configured to resonate and generate a resonant electric field.

**[0018]** The receive resonator and the capacitive balun may, responsive to the

generated electric field, be configured to resonate and generate a resonant electric field.

**[0019]** The receive resonator may comprise laterally spaced electrodes interconnected by a series inductor and the capacitive balun may comprise laterally spaced conductive elements, each conductive element being proximate to and spaced from at least one respective electrode. The conductive elements and electrodes may be in substantial alignment so that major faces of the conductive elements and electrodes face one another. The conductive elements and electrodes may also be generally planar and may have substantially similar dimensions. Alternatively, the conductive elements and electrodes may be of different dimensions and may be curved, angled and/or textured.

**[0020]** The receiver may further comprise a rectifier configured to convert the alternating signal to a direct current signal and a regulator configured to regulate the direct current signal.

## Brief Description of the Drawings

**[0021]** Embodiments will now be described more fully with reference to the accompanying drawings in which:

**[0022]** Figure 1 is a schematic layout view of a wireless electric field power transmission system;

**[0023]** Figure 2 is a schematic layout view of another wireless electric field power transmission system;

**[0024]** Figure 3 is a perspective view of a transmit balun, transmit resonator, receive balun and receive resonator arrangement forming part of the wireless electric field power transmission system of Figure 2;

**[0025]** Figure 4a is a top plan view of a series transmit inductor forming part of the wireless electric field power transmission system of Figure 2;

**[0026]** Figure 4b is a perspective view of another embodiment of a series transmit inductor;

**[0027]** Figure 4c is a perspective view of yet another embodiment of a series transmit inductor;

**[0028]** Figure 5 is a circuit diagram equivalent of the wireless electric field power transmission system of Figure 2;

**[0029]** Figure 6 is a Smith chart showing wireless electric field power transmission system impedance characteristics;

**[0030]** Figure 7 is a graph of wireless electric field power transmission system power efficiency vs. frequency;

**[0031]** Figure 8 is another Smith chart showing wireless electric field power transmission system impedance characteristics;

**[0032]** Figure 9 is another graph of wireless electric field power transmission system power efficiency vs. frequency;

**[0033]** Figure 10 is a graph of wireless electric field power transmission system efficiency vs. frequency of an exemplary system;

**[0034]** Figure 11 is a Smith chart showing transmitter impedance characteristics of a test wireless electric field power transmission system;

**[0035]** Figure 12 is a Smith chart showing receiver impedance characteristics of the exemplary system;

**[0036]** Figure 13 is a perspective view of an alternative transmit balun, transmit resonator, receive balun and receive resonator arrangement;

**[0037]** Figure 14 is a perspective view of yet another transmit balun, transmit resonator, receive balun and receive resonator arrangement;

**[0038]** Figure 15 is a schematic layout of another embodiment of a wireless electric field power transmission system;

**[0039]** Figure 16 is a perspective view of a transmit balun, transmit resonator, receive balun and receive resonator arrangement forming part of the wireless electric field power transmission system of Figure 15;

**[0040]** Figure 17 is a perspective view of another embodiment of a receiver forming part of the wireless field power transmission system of Figure 2; and

**[0041]** Figure 18 is a perspective view showing various configurations for conductive elements for use in capacitive transmit and receive baluns.

## Detailed Description of Embodiments

**[0042]** Turning now to Figure 1, a wireless electric field power transmission system is shown and is generally identified by reference numeral 20. As can be seen, wireless electric field power transmission system 20 comprises a transmitter 22 and a receiver 40 spaced apart from the transmitter 22. The transmitter 22 comprises a power source 24 electrically connected to a power inverter 26, which in turn is electrically connected across an inductive transmit balun 28. The transmitter 22 further comprises capacitive transmit electrodes ($C_{TX}$) 30, each of which is electrically connected to the inductive transmit balun 28 by a respective series inductor ($L_{TX}$) 32. The capacitive transmit electrodes ($C_{TX}$) 30 are resonated with the series inductors ($L_{TX}$) 32 at a particular operating frequency ($f_s$) to form a transmit resonator generally identified by reference numeral 34. The power inverter 26 outputs a radio frequency (RF) signal at operating frequency ($f_s$) that excites the transmit resonator 34 via the inductive transmit balun 28 causing the transmit resonator 34 to generate a resonant electric field. The inductive transmit balun 28 interconnects unbalanced and balanced systems and performs impedance transformation.

**[0043]** The receiver 40 comprises a load 42 electrically connected to a regulator 44, which in turn is electrically connected to a radio-frequency to direct current (RF-DC) rectifier 46. The RF-DC rectifier 46 is electrically connected across an inductive receive balun 48. Similar to the inductive transmit balun 28, the inductive receive balun 48 interconnects unbalanced and balanced systems and performs impedance transformation. In this embodiment, the RF-DC rectifier 46 employs ultra-fast diodes that have a low junction capacitance, a high reverse breakdown voltage and a low forward voltage drop. The RF-DC rectifier 46 may also employ synchronous MOSFETs (metal–oxide–semiconductor field-effect transistors).

**[0044]** The load 42 may take many forms such as those identified in above-incorporated U.S. Patent Application No. 13/607,474. Further exemplary loads 42 include, but are not limited to: batteries (e.g. AA, 9V and non-traditional or custom rechargeable battery formats), radio communication devices, computer batteries (e.g. desktop, laptop and tablet), phones (e.g. cordless, mobile and cellular), television sets or display panels (e.g. Plasma, LCD, LED and OLED) and home electronics (e.g. DVD players, Blu-ray players, receivers, amplifiers, all-in-one home theatre, speakers, sub-woofers, video game consoles, video game controllers,

remote control devices, televisions, computers or other monitors, digital cameras, video cameras, digital photo frames, video or image projectors and media streaming devices).

**[0045]** The receiver 40 further comprises capacitive receive electrodes ($C_{RX}$) 50, each of which is electrically connected to the inductive receive balun 48 by a respective series inductor ($L_{RX}$) 52. When the capacitive receive electrodes 50 are exposed to the resonant electric field generated by the transmit resonator 34, the capacitive receive electrodes ($C_{RX}$) 50 are resonated with the series inductor ($L_{RX}$) 52 at the same operating frequency ($f_s$) as the transmit resonator 34 to form a receive resonator generally identified by reference numeral 54.

**[0046]** In this embodiment, the inductive transmit and receive baluns 28 and 48, respectively, comprise a ferrite core and have a turn ratio of slightly higher than 1:1 for impedance matching purposes. Although these baluns perform well, they disadvantageously require significant physical space. Furthermore, these baluns are intrinsically limited in operating frequency and power levels. In addition, at higher power levels, these baluns heat up increasing the risk of damage to the baluns or other components of the wireless electric field power transmission system.

**[0047]** Turning now to Figure 2, an alternative wireless electric field power transmission system 120 is shown. As can be seen, wireless electric field power transmission system 120 comprises a transmitter 122 and a receiver 140 spaced apart from the transmitter 122. The transmitter 122 comprises a power source 124 electrically connected to a power inverter 126, which in turn is electrically connected across a capacitive transmit balun ($C_{drive}$) 128. Collectively, the power source 124 and power inverter 126 form an RF source 127. The transmitter 122 further comprises capacitive transmit electrodes ($C_{TX}$) 130 that are electrically connected by a series transmit inductor ($L_{TX}$) 132 and that are capacitively coupled to the capacitive transmit balun 128. The capacitive transmit electrodes 130 are resonated with the series transmit inductor 132 at a particular operating frequency ($f_s$) to form a transmit resonator generally identified by reference numeral 134.

**[0048]** The receiver 140 comprises a load 142 electrically connected to a regulator 144, which in turn is electrically connected to an RF-DC rectifier 146. The RF-DC rectifier 146 is electrically connected across a capacitive receive balun ($C_{load}$) 148. Similar to the previous embodiment, the RF-DC rectifier 146 employs ultra-fast

diodes that have a low junction capacitance, a high reverse breakdown voltage and a low forward voltage drop. The RF-DC rectifier 146 may also employ synchronous MOSFETs (metal–oxide–semiconductor field-effect transistors). The load 142 may take many forms such as those identified in above-incorporated U.S. Patent Application No. 13/607,474. Further exemplary loads 142 include, but are not limited to: batteries (e.g. AA, 9V and non-traditional or custom rechargeable battery formats), radio communication devices, computer batteries (e.g. desktop, laptop and tablet), phones (e.g. cordless, mobile and cellular), television sets or display panels (e.g. Plasma, LCD, LED and OLED) and home electronics (e.g. DVD players, Blu-ray players, receivers, amplifiers, all-in-one home theatre, speakers, sub-woofers, video game consoles, video game controllers, remote control devices, televisions, computers or other monitors, digital cameras, video cameras, digital photo frames, video or image projectors and media streaming devices).

**[0049]** The receiver 140 further comprises capacitive receive electrodes ($C_{RX}$) 150 that are electrically connected by a series receive inductor ($L_{RX}$) 152 and that are capacitively coupled to the capacitive receive balun 148. The capacitive receive electrodes 150 are resonated with the series receive inductor 152 at the particular operating frequency ($f_s$) to form a receive resonator generally identified by reference numeral 154.

**[0050]** Turning now to Figure 3, the capacitive transmit balun 128, transmit resonator 134, capacitive receive balun 148 and receive resonator 154 are better illustrated. The transmitter 122 and receiver 140 are spaced apart by a distance $d_{TR}$. In this embodiment, the capacitive transmit balun 128 comprises a pair of laterally spaced, elongate elements formed of electrically conductive material. The conductive elements are in the form of generally rectangular, planar plates. The capacitive transmit electrodes 130 of the transmit resonator 134 are also in the form of elongate generally rectangular, planar plates formed of electrically conductive material. Each plate of the capacitive transmit balun 128 is proximate to and aligned with a respective capacitive transmit electrode 130 so that major surfaces 136 and 138 of the plates and capacitive transmit electrodes 130 face one another and are separated by a distance $d_1$. In this embodiment, the areas of the major surfaces 136 and 138 are equal or near-equal, that is the dimensions of the plates of the capacitive transmit balun 128 and the capacitive transmit electrodes 130 are basically the same.

**[0051]** The capacitive receive balun 148 comprises a pair of laterally spaced, elongate elements formed of electrically conductive material. The conductive elements are in the form of generally rectangular, planar plates. The capacitive receive electrodes 150 of receive resonator 154 are also in the form of elongate generally rectangular, planar plates formed of electrically conductive material. Each plate of the capacitive receive balun 148 is proximate to and aligned with a respective capacitive receive electrode 150 so that major surfaces 156 and 158 of the plates and capacitive receive electrodes 150 face one another and are separated by a distance $d_2$. In this embodiment, the areas of the major surfaces 156 and 158 are equal or near-equal, that is the dimensions of the plates of the capacitive receive balun 148 and the capacitive receive electrodes 150 are basically the same.

**[0052]** Turning now to Figure 4a, the series transmit inductor ($L_{TX}$) 132 is better illustrated. As can be seen, in this embodiment, the series transmit inductor ($L_{TX}$) 132 is a flat spiral or pancake coil. The series transmit inductor ($L_{TX}$) 132 has a high quality factor (Q-factor) and is configured to create a high Q-factor resonance with the capacitive transmit electrodes ($C_{TX}$) 130 at the operating frequency ($f_s$). A high Q-factor means that the amount of energy stored is greater than the amount of energy dissipated. High Q-factor resonance increases the voltage on the capacitive transmit electrodes ($C_{TX}$) 130 compared to the applied voltage. In this embodiment, the series receive inductor ($L_{RX}$) 152 is similarly a flat spiral or pancake coil. The series receive inductor ($L_{RX}$) 152 also has a high Q-factor and is configured to create a high Q-factor resonance with the capacitive receive electrodes ($C_{RX}$) 150 at the operating frequency ($f_s$).

**[0053]** The series transmit inductor ($L_{TX}$) 132 and the series receive inductor ($L_{RX}$) 152 may however, take different forms as shown in Figures 4b and 4c. In Figure 4b, the series transmit inductor ($L_{TX}$) 132 is in the form of a toroidal transmit inductor ($L_{TX}$) 132a and in Figure 4c, the series transmit inductor is in the form of a cylindrical spiral transmit inductor ($L_{TX}$) 132b. Similar to the series transmit inductor ($L_{TX}$) 132, the series receive inductor ($L_{RX}$) 152 may also be in the form of a toroidal receive inductor ($L_{RX}$) or a cylindrical spiral receive inductor ($L_{RX}$).

**[0054]** The operation of the wireless electric field power transmission system 120 will now be described. During operation, the RF power source 127 comprises power source 124 and power inverter 126, and outputs an RF signal at operating frequency ($f_s$), and this RF signal is then applied across the plates of the capacitive transmit

balun ($C_{drive}$) 128 thereby to excite the capacitive transmit balun ($C_{drive}$) 128. The excited capacitive transmit balun ($C_{drive}$) 128 in turn generates an electric field in a volume that surrounds the plates of the capacitive transmit balun ($C_{drive}$) 128. When the capacitive transmit resonator 134 is within the generated electric field, the capacitive transmit electrodes ($C_{TX}$) 130 and the capacitive transmit balun ($C_{drive}$) 128 resonate with the series inductor ($L_{TX}$) 132 at the operating frequency ($f_s$) thereby generating a resonant electric field that extends to the receive resonator 154.

**[0055]** With the receive resonator 154 in the generated resonant electric field, the capacitive receive electrodes ($C_{RX}$) 150 begin to resonate with the series receive inductor ($L_{RX}$) 152 resulting in the generation of a resonant electric field in a volume that surrounds the plates of the capacitive receive balun ($C_{load}$) 148. When the capacitive receive balun ($C_{load}$) 148 is within the generated resonant electric field, the capacitive receive balun ($C_{load}$) 148 and the capacitive receive electrodes ($C_{RX}$) 150 resonate with the series inductor ($L_{RX}$) 152 at the operating frequency ($f_s$) resulting in the capacitive receive balun ($C_{load}$) 148 outputting an RF signal that is conveyed to the RF-DC rectifier 146.

**[0056]** The RF-DC rectifier 146 in turn converts the RF signal to a DC signal which is then regulated at the regulator 144 and conveyed to the load 142.

**[0057]** A circuit diagram equivalent of the wireless electric field power transmission system 120 is depicted in Figure 5. As described above, the RF signal, at operating frequency ($f_s$), that is output by RF source 127 is used to excite the capacitive transmit balun ($C_{drive}$) 128 and this excitation results in the generation of an electric field that surrounds the plates of the capacitive transmit balun ($C_{drive}$) 128 and the capacitive transmit electrodes ($C_{TX}$) 130. The coupling coefficient between the capacitive transmit balun ($C_{drive}$) 128 and the capacitive transmit electrodes ($C_{TX}$) 130 is represented by $k_{12}$ and is given by:

$$k_{12} = \frac{M_{12}}{\sqrt{C_{drive} \times C_{TX}}}$$

where $M_{12}$ is the mutual capacitance between the capacitive transmit balun 128 and the capacitive transmit electrodes 130.

**[0058]** The coupling coefficient between the capacitive transmit electrodes 130 and the capacitive receive electrodes 150 is represented by $k_{23}$ and is given by:

$$k_{23} = \frac{M_{23}}{\sqrt{C_{TX} \times C_{RX}}}$$

where $M_{23}$ is the mutual capacitance between the capacitive transmit electrodes 130 and the capacitive receive electrodes 150.

**[0059]** The coupling coefficient between the capacitive receive electrodes 150 and the capacitive receive balun 148 is represented by $k_{34}$ and is given by:

$$k_{34} = \frac{M_{34}}{\sqrt{C_{RX} \times C_{load}}}$$

where $M_{34}$ is the mutual capacitance between the capacitive receive electrodes 150 and the capacitive receive balun 148.

**[0060]** As will be appreciated, varying the separation distances $d_1$ and $d_2$, varies the coupling coefficients by altering the mutual capacitance. Also, since the receiver 140 is in the near field of the transmitter 122, the impedance seen by the transmitter 122 varies as the separation distance $d_{TR}$ between the transmitter 122 and receiver 140 varies, resulting in a change in the resonant frequency of the wireless electric field power transmission system 120. This impedance can be adjusted to the impedance $R_S$ of the RF source 127 by varying the separation distance $d_1$ or by increasing the length of the plates of the capacitive transmit balun ($C_{drive}$) 128.

**[0061]** Similarly, the impedance seen by the receiver 140 also varies as the separation distance $d_{TR}$ between the transmitter 122 and receiver 140 varies. This impedance can be adjusted to the impedance of the load 142 by varying the separation distance $d_2$ or by increasing the length of the plates of the capacitive receive balun ($C_{load}$) 148.

**[0062]** Turning back to Figure 3, the length overlap ($L_{ol}$) of the transmitter 122 is defined as the amount of overlap between the major surfaces 136 of the plates of the capacitive transmit balun ($C_{drive}$) 128 and the major surfaces 138 of the capacitive transmit electrodes ($C_{TX}$) 130 along the lengths of those major surfaces. The width overlap ($W_{ol}$) of the transmitter 122 is defined as the amount of overlap between the major surfaces 136 of the plates of the capacitive transmit balun ($C_{drive}$) 128 and the major surfaces 138 of the capacitive transmit electrodes ($C_{TX}$) 130 along the widths of those major surfaces.

**[0063]** Similarly, the length overlap ($L_{ol}$) of the receiver 140 is defined as the

amount of overlap between the major surfaces 156 of the plates of the capacitive receive balun ($C_{load}$) 148 and the major surfaces 158 of the capacitive receive electrodes ($C_{RX}$) 150 along the lengths of those major surfaces. The width overlap ($W_{ol}$) of the receiver 140 is defined as the amount of overlap between the major surfaces 156 of the plates of the capacitive receive balun ($C_{load}$) 148 and the major surfaces 158 of the capacitive receive electrodes ($C_{RX}$) 150 along the widths of those major surfaces. In this embodiment, the length overlaps ($L_{ol}$) and the width overlaps ($W_{ol}$) of the transmitter 122 and receiver 140 are the same.

**[0064]** According to coupled mode theory, when the transmitter 122 and receiver 140 are resonating at their fundamental frequencies, the resulting operating frequency depends on the coupling between the transmitter 122 and receiver 140. If there is strong coupling then there are two modes of operation at two different frequencies. This phenomenon is referred to as frequency splitting. If the coupling is weak, then these two modes converge to a single mode of operation at a single frequency. Frequency splitting is present in simulations described below.

**[0065]** Electromagnetic field simulations using CST Microwave Studio software were performed to determine the impedance requirements of the wireless electric field power transmission system 120 at a particular operating frequency ($f_s$). Figures 6 to 9 show the results of the electromagnetic field simulations for determining the impedance requirements of the wireless electric field power transmission system 120 at an operating frequency ($f_s$) of 7 MHz. As shown in the Smith chart of Figure 6, a frequency sweep from 5 to 8 MHz yields matched impedance between the transmitter 122 and receiver 140 at the points marked 1 and 2. The efficiency of the wireless electric field power transmission system 120 at these points is depicted in Figure 7 in which the frequency at point 2 is shown to be approximately 7 MHz. The corresponding impedance requirement from the Smith chart of Figure 6 at point 2 is approximately 99 Ohms. This impedance was achieved with separation distances $d_1$ and $d_2$ equal to 1.57 mm and length overlaps ($L_{ol}$) equal to 120 mm.

**[0066]** As shown in the Smith chart of Figure 8, a frequency sweep from 1 to 12 MHz yields matched impedance between the transmitter 122 and the receiver 140 at the points marked 1 and 2. The efficiency of the wireless electric field power transmission system 120 at these points is depicted in Figure 9 in which the frequency at point 1 is shown to be approximately 7 MHz. The corresponding impedance requirement from the Smith chart of Figure 8 at point 1 is approximately

62 Ohms. This impedance was achieved with separation distances $d_1$ and $d_2$ equal to 0.867 mm and length overlaps ($L_{ol}$) equal to 60 mm.

**[0067]** In the above simulations, the widths of the plates of the capacitive transmit balun ($C_{drive}$) 128, the widths of the capacitive transmit electrodes ($C_{TX}$) 130, the widths of the plates of the capacitive receive balun ($C_{load}$) 148 and the widths of the capacitive receive electrodes ($C_{RX}$) 150 were equal. Those of skill in the art will however appreciate that these widths can be varied.

**[0068]** As will be appreciated from the results of the simulations, it is clear that both the resonant frequency ($f_s$) of the wireless electric field power transmission system 120 and the impedance of the transmitter 122 and receiver 140 can be matched by changing the distances $d_1$, $d_2$ and the lengths of the major surfaces 136 and 156 of the plates of the capacitive transmit balun ($C_{drive}$) 128 and the capacitive receive balun ($C_{load}$) 148, respectively.

**[0069]** The use of the capacitive transmit balun ($C_{drive}$) 128 and the capacitive receive balun ($C_{load}$) 148 allows the sizes of capacitive transmit electrodes ($C_{TX}$) 130 and the capacitive receive electrodes ($C_{RX}$) 150 to be reduced compared to inductive baluns since the capacitive transmit and receive baluns ($C_{drive}$) 128 and ($C_{load}$) 148 are capacitive rather than inductive and require less capacitance to reach a resonant state. The use of the capacitive transmit balun ($C_{drive}$) 128 and the capacitive receive balun ($C_{load}$) 148 also eliminates the need for inductive baluns and reduces the number of inductors required at the transmit resonator 134 and the receive resonator 154. The results in a transmitter 122 and a receiver 140 that are smaller, cheaper and simpler to design.

**[0070]** An exemplary wireless electric field power transmission system in accordance with Figures 2 and 3 was constructed with the following parameters: an operating frequency of approximately 27 MHz and a distance $d_{TR}$ of approximately 10 cm. With regard to the transmitter, the following parameters were used: a distance of approximately 15 cm between the capacitive transmit electrodes, an electrode length of approximately 33 cm for each electrode of the capacitive transmit electrodes, a length overlap $L_{ol}$ of approximately 1.7 cm, a width overlap $W_{ol}$ of approximately 5 cm, a distance $d_1$ of approximately 0.24 cm, a series transmit inductor $L_{TX}$ having an inductance of approximately 5.9 $\mu H$, and a quality factor of approximately 300. With regard to the receiver, the following parameters were used:

a distance of approximately 15 cm between the capacitive receive electrodes, an electrode length of approximately 33 cm for each electrode of the capacitive receive electrodes, a length $L_{ol}$ of approximately 2.6 cm, a width overlap $W_{ol}$ of approximately 5 cm, a distance $d_2$ of approximately 0.54 cm, a series receive inductor $L_{RX}$ having an inductance of approximately 5.1 $\mu H$, and a quality factor of approximately 250. Experimental data was collected using a Copper Mountain Technologies™ PLANAR 808/1 four port Vector Network Analyzer (VNA). The frequency was swept from 20 MHz to 30 MHz to measure the system impedances and efficiencies at various operating frequencies. As shown in Figure 10, the frequency sweep from 20 to 30 MHz yields matched maximum efficiency between the transmitter and receiver at approximately 26.85 MHz, point 1. The corresponding impedance requirement from the Smith chart of Figure 11 for the transmitter at point 1 is approximately 63 Ohms. The corresponding impedance requirement from the Smith chart of Figure 12 for the receiver at point 1 is approximately 56 Ohms.

**[0071]** In the embodiment of Figure 2, the plates of the capacitive transmit balun 128 and the capacitive transmit electrodes 130 have the same dimensions and are arranged so that their facing major surfaces 136 and 138 are in substantially perfect alignment. Similarly, the plates of the capacitive receive balun 148 and the capacitive receive electrodes 150 have the same dimensions and are arranged so that their facing major surfaces 156 and 158 are in substantially perfect alignment. Those of skill in the art will however appreciate that variations are possible.

**[0072]** For example, another embodiment of a capacitive transmit balun, capacitive transmit electrodes, capacitive receive electrodes and capacitive receive balun arrangement is shown in Figure 13. The embodiment shown in Figure 13 is similar to the embodiment shown in Figure 3 and as such like components are referred to with the same reference numerals with "100" added for clarity. In this embodiment, the plates of the capacitive transmit balun 228 are shorter or smaller in dimension than the capacitive transmit electrodes 230 and the plates of the capacitive receive balun 248 are shorter or smaller in dimension than the capacitive receive electrodes 250. The change in impedance caused by the change in the lengths of the plates of the capacitive transmit balun 228 and the plates of the capacitive receive balun 248 can be offset by changing the separation distances $d_1$ and $d_2$. As with the embodiment shown in Figure 3, the width overlaps $W_{ol}$, length overlaps $L_{ol}$, distances $d_1$ and $d_2$ and distance $d_{TR}$ may be adjusted as needed.

**[0073]** Still other arrangements are possible. As shown in Figure 14, rather than using a capacitive transmit balun ($C_{drive}$) 128 to excite the capacitive transmit electrodes 130, an inductive transmit balun may be employed generally identified by reference numeral 360. The embodiment shown in Figure 14 is similar to the embodiment shown in Figure 3 and as such like components are referred to with the same reference numerals with "200" added for clarity. Each capacitive transmit electrode 330 is connected to the inductive transmit balun 360 via a respective series inductor 362. This makes placing the transmitter 322 on a non-flat surface more difficult since the transmit inductors 362 suffer from a loss of inductance and a reduction in quality factor (Q) if they are bent to conform to non-flat surfaces.

**[0074]** Similar to the embodiment of Figure 13, in this embodiment, the plates of the capacitive receive balun 348 are shorter or smaller in dimension than the capacitive receive electrodes 350. Those of skill in the art will however appreciate that the plates of the capacitive receive balun 348 may be similar in dimension to the capacitive receive electrodes 350. Also, rather than replacing the capacitive transmit balun 128 with an inductive transmit balun 360, a capacitive transmit balun may be employed and the capacitive receive balun 348 may be replaced with an inductive receive balun.

**[0075]** Turning now to Figures 15 and 16, another embodiment of a wireless electric field power transmission system is shown that is similar to the embodiment shown in Figure 2 and as such like components are referred to with the same reference numerals with "300" added for clarity. In this embodiment, the transmitter 422 and receiver 440 further comprise series inductors ($L_s$) for additional impedance and resonance control. As can be seen, in the transmitter 422, the power inverter 426 is connected directly to one plate of the capacitive transmit balun 428 ($C_{drive}$) and is connected to the other plate of the capacitive transmit balun 428 ($C_{drive}$) via a series inductor ($L_s$) 464.

**[0076]** In the receiver 440, the RF-DC rectifier 446 is connected directly to one plate of the capacitive receive balun ($C_{load}$) 448 and is connected to the other plate of the capacitive receive balun 448 via a series inductor (*Ls*) 466. The configurations of the plates of the capacitive transmit balun and capacitive transmit electrodes and the plates of the capacitive receive baluns and capacitive receive electrodes as shown are similar to the arrangement of Figure 13. Those of skill in the art will however appreciate that the configurations of the plates of the capacitive transmit balun and

capacitive transmit electrodes and the plates of the capacitive receive baluns and capacitive receive electrodes may vary and for example, take the form similar to the arrangement of Figure 3. The various dimensions comprising width overlaps $W_{ol}$, length overlaps $L_{ol}$, distances $d_1$ and $d_2$ and distance $d_{TR}$ may be adjusted as needed.

**[0077]** During operation, the power inverter 426 when driven by the power source 424 outputs an RF signal at operating frequency ($f_s$), and this RF signal is then applied across the plates of the capacitive transmit balun ($C_{drive}$) 428 thereby to excite the capacitive transmit balun ($C_{drive}$) 428. The excited capacitive transmit balun ($C_{drive}$) 428 resonates with the series inductor ($L_s$) 464 at the operating frequency ($f_s$) thereby generating a resonant electric field. When the capacitive transmit resonator 434 is within the generated resonant electric field, the capacitive transmit electrodes ($C_{TX}$) 430 and the capacitive transmit balun ($C_{drive}$) 428 resonate with the series inductor ($L_{TX}$) 432 and ($L_s$) 464 at the operating frequency ($f_s$) thereby generating a resonant electric field that extends to the receive resonator 454.

**[0078]** With the receive resonator 454 in the generated resonant electric field, the capacitive receive electrodes ($C_{RX}$) 450 begin to resonate with the series receive inductor ($L_{RX}$) 452 resulting in the generation of a resonant electric field in a volume that surrounds the plates of the capacitive receive balun ($C_{load}$) 448. When the capacitive receive balun ($C_{load}$) 448 is within the generated resonant electric field, the capacitive receive balun ($C_{load}$) 448 and the capacitive receive electrodes ($C_{RX}$) 450 resonate with the series inductor ($L_{RX}$) 152 at the operating frequency ($f_s$) resulting in the capacitive receive balun ($C_{load}$) 448 outputting an RF signal that is conveyed to the RF-DC rectifier 446.

**[0079]** Figure 17 depicts an alternative capacitive receive electrode and capacitive receive balun arrangement. This embodiment is similar to the receiver 140 of the embodiment shown in Figure 3 and as such like components are referred to with the same reference numerals with “400” added for clarity. Similar to the arrangement of Figure 13, the plates of the capacitive receive balun 548 are shorter or smaller in dimension than the capacitive receive electrodes 550 although if desired the plates of the capacitive receive balun 548 and the capacitive receive electrodes 550 may be of the same dimension. In this embodiment however, rather than being planar, the plates of the capacitive receive balun 548 and the capacitive receive electrodes 550 are curved.

**[0080]** Those of skill in the art will appreciate that the curved plate and electrode arrangement can be applied to the transmitter.

**[0081]** While the conductive elements of the capacitive transmit and receive baluns and the capacitive transmit and receive electrodes have been shown and described as taking the form of generally rectangular parallel plates, those of skill in the art will appreciate that alternatives are possible. The conductive elements of the capacitive transmit and receive baluns and the capacitive transmit and receive electrodes may take various forms. For example, Figure 18 depicts various geometrical shapes for the conductive elements of the capacitive transmit and receive baluns and the capacitive transmit and receive electrodes. As can be seen, the conductive elements of the capacitive transmit and receive baluns and electrodes can have a square shape, an arrow shape, a convex circular shape, a rhombus shape with curved sides, a circular shape or a triangular shape. As will be appreciated, the conductive elements of the capacitive transmit and receive baluns and the capacitive transmit and receive electrodes may be angled, curved and/or textured in various configurations.

**[0082]** Although the wireless electric field power transmission system is shown as comprising a pair of capacitive transmit electrodes and a pair of capacitive receive electrodes, those of skill in the art will appreciate that more than two capacitive transmit electrodes and more than two capacitive receive electrodes may be employed. Increasing the number of capacitive transmit electrodes ($C_{TX}$) 130 and increasing the number of capacitive receive electrodes ($C_{RX}$) 150 reduces Eddy current loss.

**[0083]** Those of skill in the art will appreciate that the wireless power transmission system can be used in a variety of applications including those identified in above-incorporated U.S. Patent Application No. 13/607,474. Further, applications include, but are not limited to, integrating parts or all of the wireless power transmission system into: a backpack, a vehicle (e.g. fire truck, bus, military vehicles, Unmanned Autonomous Vehicles (UAVs) electric car and hybrid car), a radio communication device, a military base camp, an airplane, a table, a computer (e.g. laptop, desktop and tablet computer), a container, a flat surface (e.g. tables, desks, counters, shelves, walls, floors, ceilings and doors), a phone (e.g. cordless, mobile and cellular), a television set or display panel (e.g. Plasma, LCD, LED and OLED), home electronics (e.g. DVD players, Blu-ray players, receivers, amplifiers, all-in-one home

theatre, speakers, sub-woofers, video game consoles, video game controllers, remote control devices, televisions, computers or other monitors, digital cameras, video cameras, digital photo frames, video or image projectors and media streaming devices), and a public space or common area.

**[0084]** Although wireless electric field power transmission systems are shown as comprising a power source connected to a power inverter with the power inverter outputting an RF signal that excites the capacitive balun, those of skill in the art will appreciate that other configurations are possible. For example, the power inverter may be omitted and a power source that outputs an alternating or RF signal to excite the capacitive balun may be employed.

**[0085]** Although embodiments have been described above with reference to the figures, those of skill in the art will appreciate that variations and modifications may be made without departing from the scope thereof as defined by the appended claims.

**What is claimed is**:

1. A wireless electric field power transmission system comprising:

a transmitter comprising a transmit resonator and a transmit capacitive balun; and

at least one receiver comprising a receive resonator and a receive capacitive balun, wherein, via electric field coupling:

the transmit capacitive balun is configured to transfer power to the transmit resonator,

in response, the transmit resonator is configured to transfer power to the receive resonator, and

the receive capacitive balun is configured to extract power from the receive resonator.

2. A method of wirelessly transferring power, the method comprising:

delivering power from a source to a transmit resonator via a transmit capacitive balun via electric field coupling;

in response, transferring power from the transmit resonator to a receive resonator via electric field coupling; and

extracting power from the receive resonator via a receive capacitive balun via electric field coupling.

3. A transmitter for wirelessly transferring power, the transmitter comprising:

a capacitive balun configured to receive an alternating signal and in response generate an electric field; and

a transmit resonator, responsive to the electric field generated by the capacitive balun, configured to resonate and generate an electric field to a receiver.

4. The transmitter of claim 3, wherein the transmit resonator, responsive to the electric field generated by the capacitive balun, is configured to resonate and generate a resonant electric field to the receiver.

5. The transmitter of claim 3, wherein the capacitive balun and the transmit resonator, responsive to the electric field generated by the capacitive balun, are configured to resonate and generate a resonant electric field to the receiver.

6. The transmitter of claim 3, wherein the capacitive balun is configured to receive the alternating signal and in response generate a resonant electric field.

7. The transmitter of claim 6, wherein the transmit resonator, responsive to the resonant electric field generated by the capacitive balun, is configured to resonate and generate the electric field to the receiver.

8. The transmitter of claim 6, wherein the transmit resonator, responsive to the resonant electric field generated by the capacitive balun, is configured to resonate and generate a resonant electric field to the receiver.

9. The transmitter of any one of claims 3 to 8, wherein the transmit resonator comprises laterally spaced electrodes interconnected by a series inductor.

10. The transmitter of claim 9, wherein said capacitive balun comprises laterally spaced conductive elements, each conductive element being proximate to and spaced from at least one respective electrode.

11. The transmitter of claim 10, wherein the conductive elements and electrodes are in substantial alignment so that major faces of the conductive elements and electrodes face one another.

12. The transmitter of claim 10 or 11, wherein the conductive elements and electrodes are generally planar.

13. The transmitter of claim 10 or 11, wherein the conductive elements and electrodes are curved, angled and/or textured.

14. The transmitter of any one of claims 10 to 13, wherein the conductive elements and electrodes have substantially similar dimensions.

15. The transmitter of any one of claims 10 to 13, wherein the conductive elements and electrodes are of different dimensions and/or different geometries.

16. The transmitter of any one of claims 3 to 15, further comprising a power inverter connected across the capacitive balun, said power inverter configured to output the alternating signal that excites the capacitive balun.

17. The transmitter of any one of claims 3 to 15, further comprising a source configured to generate the alternating signal that excites the capacitive balun.

18. The transmitter of any one of claims 3 to 17, wherein the alternating signal is a radio frequency (RF) signal.

19. A receiver for wirelessly receiving power, the receiver comprising:

a receive resonator configured to resonate in the presence of a generated electric field; and

a capacitive balun capacitively coupled to the receive resonator and configured to output an alternating signal in response to resonance of the receive resonator.

20. The receiver of claim 19, wherein the receive resonator is configured to resonate in the presence of a generated resonant electric field.

21. The receiver of claim 20, wherein the receive resonator, responsive to the generated resonant electric field, is configured to resonate and generate an electric field.

22. The receiver of claim 20, wherein the receive resonator, responsive to the generated resonant electric field, is configured to resonate and generate a resonant electric field.

23. The receiver of claim 22, wherein the receive resonator and the capacitive balun, responsive to the resonant electric field generated by the receive resonator, are configured to resonate and generate a resonant electric field.

24. The receiver of claim 19, wherein the receive resonator and the capacitive balun, responsive to the generated electric field, are configured to resonate and generate a resonant electric field.

25. The receiver of any one of claims 19 to 24, wherein the receive resonator comprises laterally spaced electrodes interconnected by a series inductor.

26. The receiver of claim 25, wherein said capacitive balun comprises laterally spaced conductive elements, each capacitive element being proximate to and spaced from at least one respective electrode.

27. The receiver of claim 26, wherein the conductive elements and electrodes are in substantial alignment so that major faces of the conductive elements and electrodes face one another.

28. The receiver of claim 26 or 27, wherein the conductive elements and electrodes are generally planar.

29. The receiver of claim 26 or 27, wherein the conductive elements and electrodes are curved, angled and/or textured.

30. The receiver of any one of claims 26 to 29, wherein the conductive elements and electrodes have substantially similar dimensions.

31. The receiver of any one of claims 26 to 29, wherein the conductive elements and electrodes are of different dimensions and/or different geometries.

32. The receiver of any one of claims 19 to 31, further comprising a rectifier configured to convert the alternating signal to a direct current signal.

33. The receiver of claim 32, further comprising a regulator configured to regulate the direct current signal.

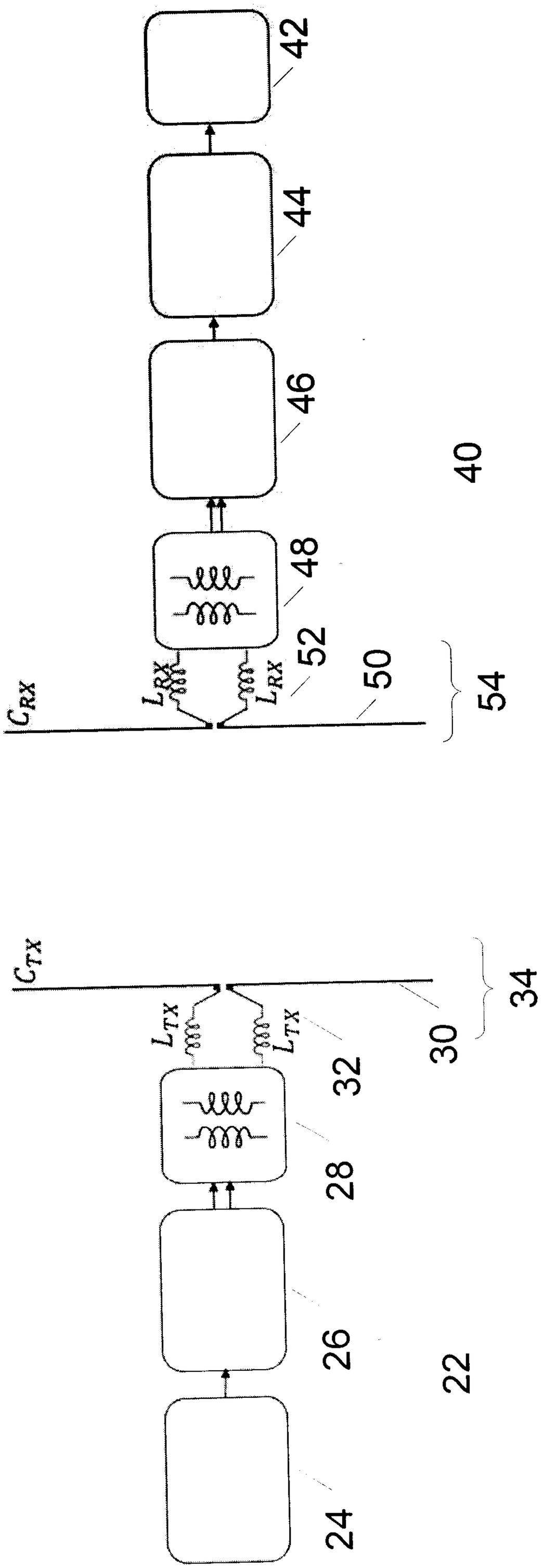

42
44
46
48
52
50
54
40
$L_{RX}$
$L_{RX}$
$C_{RX}$
$L_{TX}$
$L_{TX}$
$C_{TX}$
32
30
34
28
26
24
22
20

Figure 1

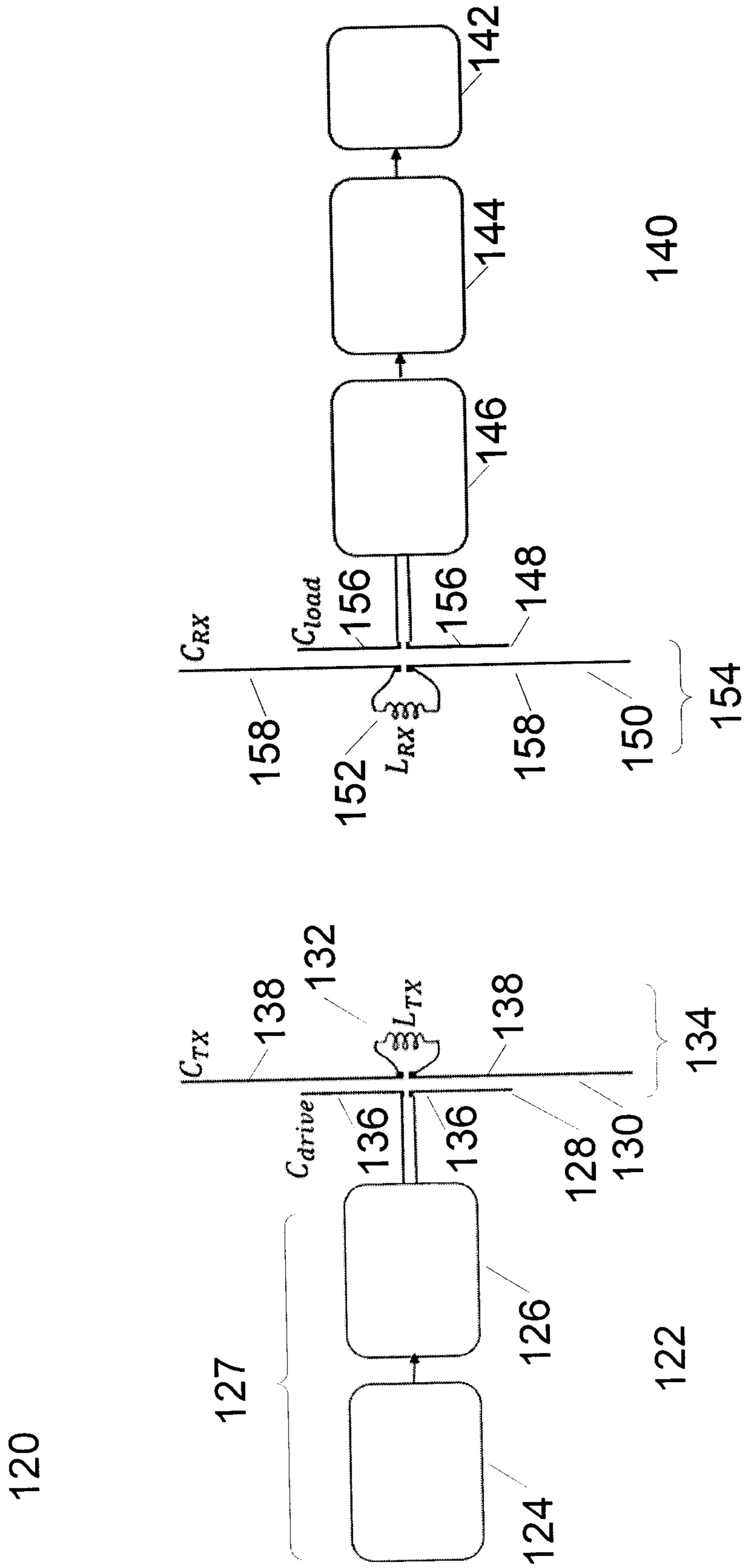

120
122
124
126
127
128
130
132
134
136
138
140
142
144
146
148
150
152
154
156
158
$C_{drive}$
$C_{load}$
$C_{RX}$
$C_{TX}$
$L_{RX}$
$L_{TX}$

Figure 2

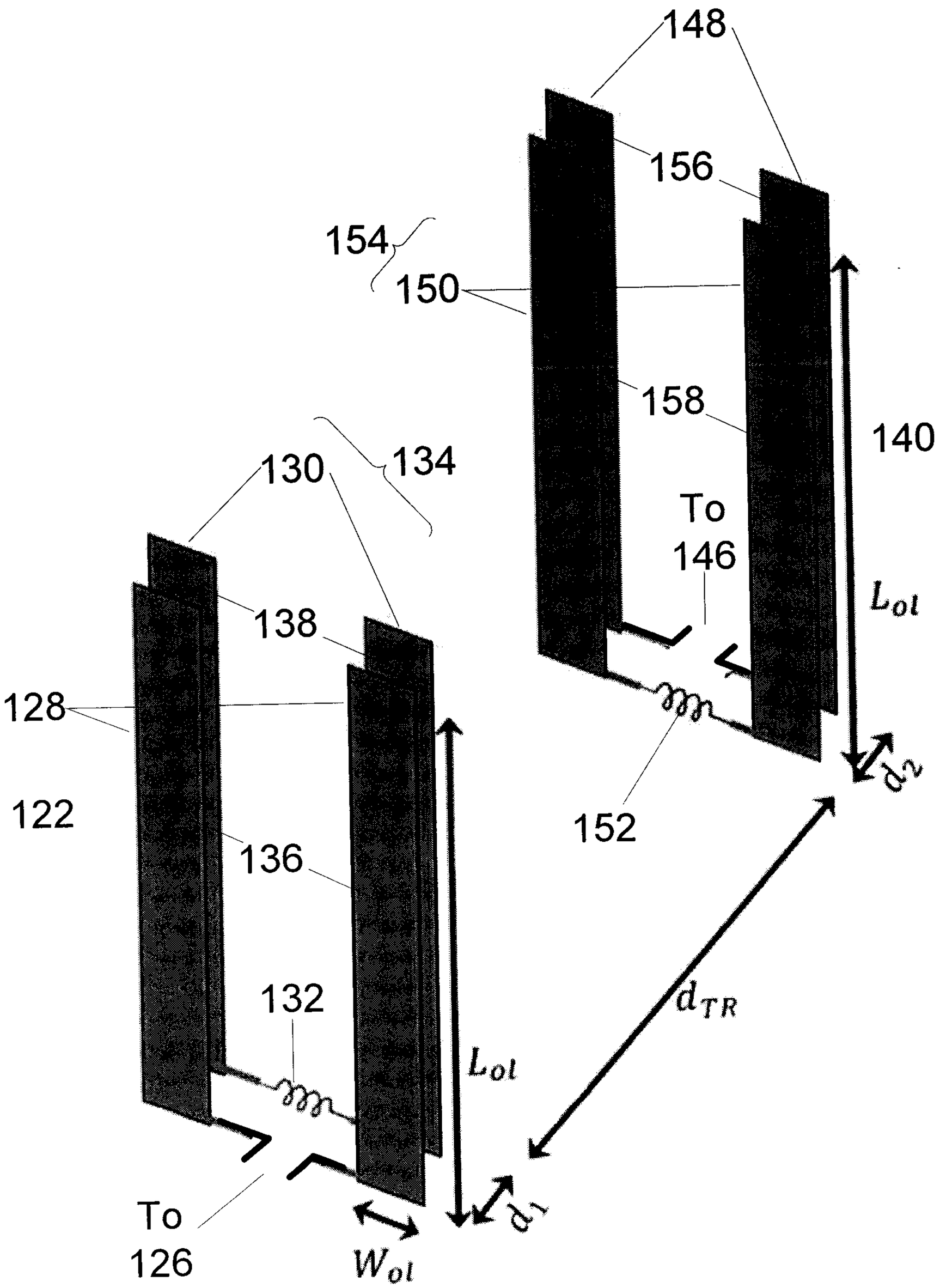

148
156
154
150
158
140
To
146
$L_{ol}$
$d_2$
152
$d_{TR}$
130
134
138
128
122
136
132
$L_{ol}$
To
$d_1$
126
$W_{ol}$

Figure 3

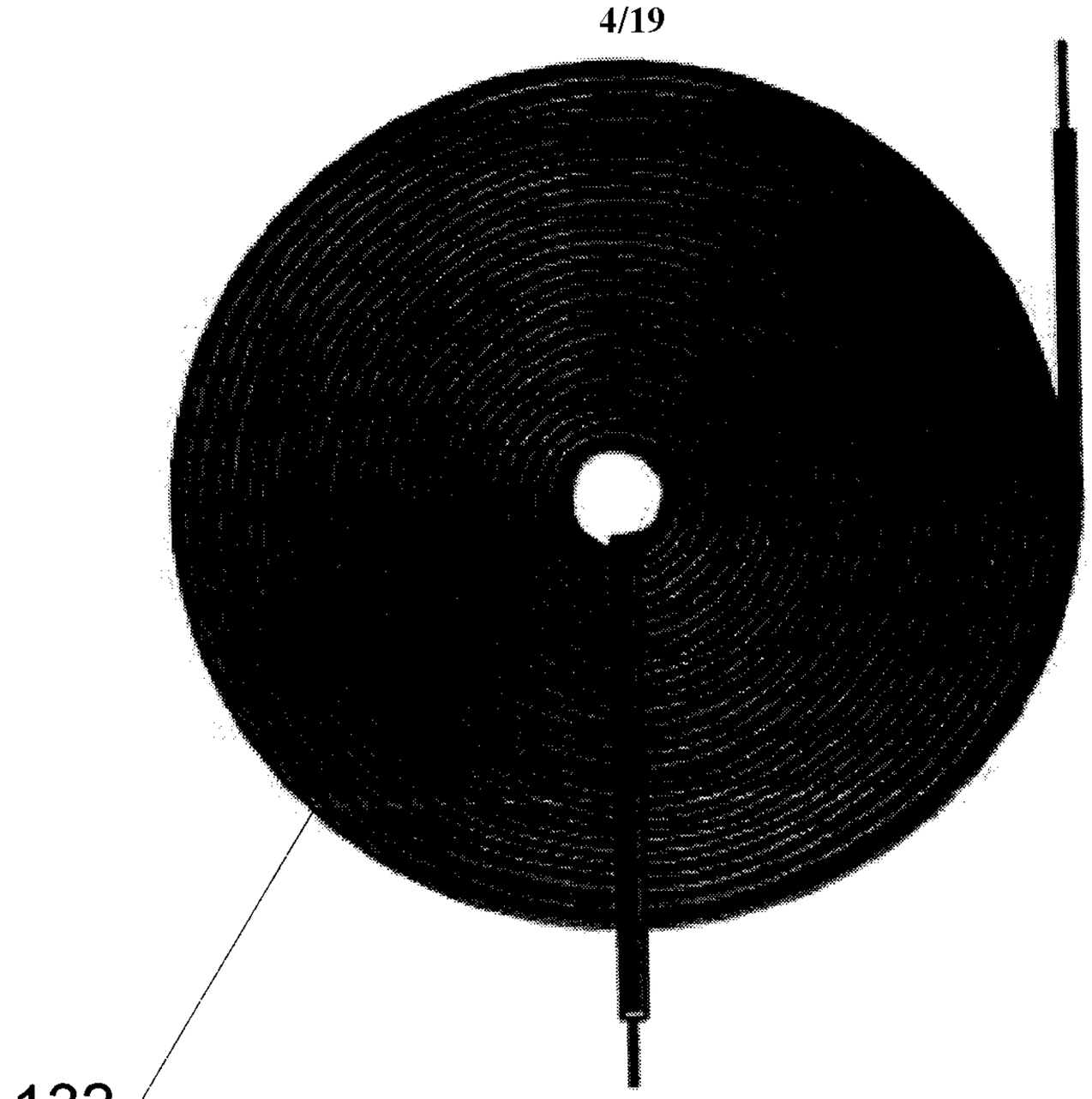



Figure 4a

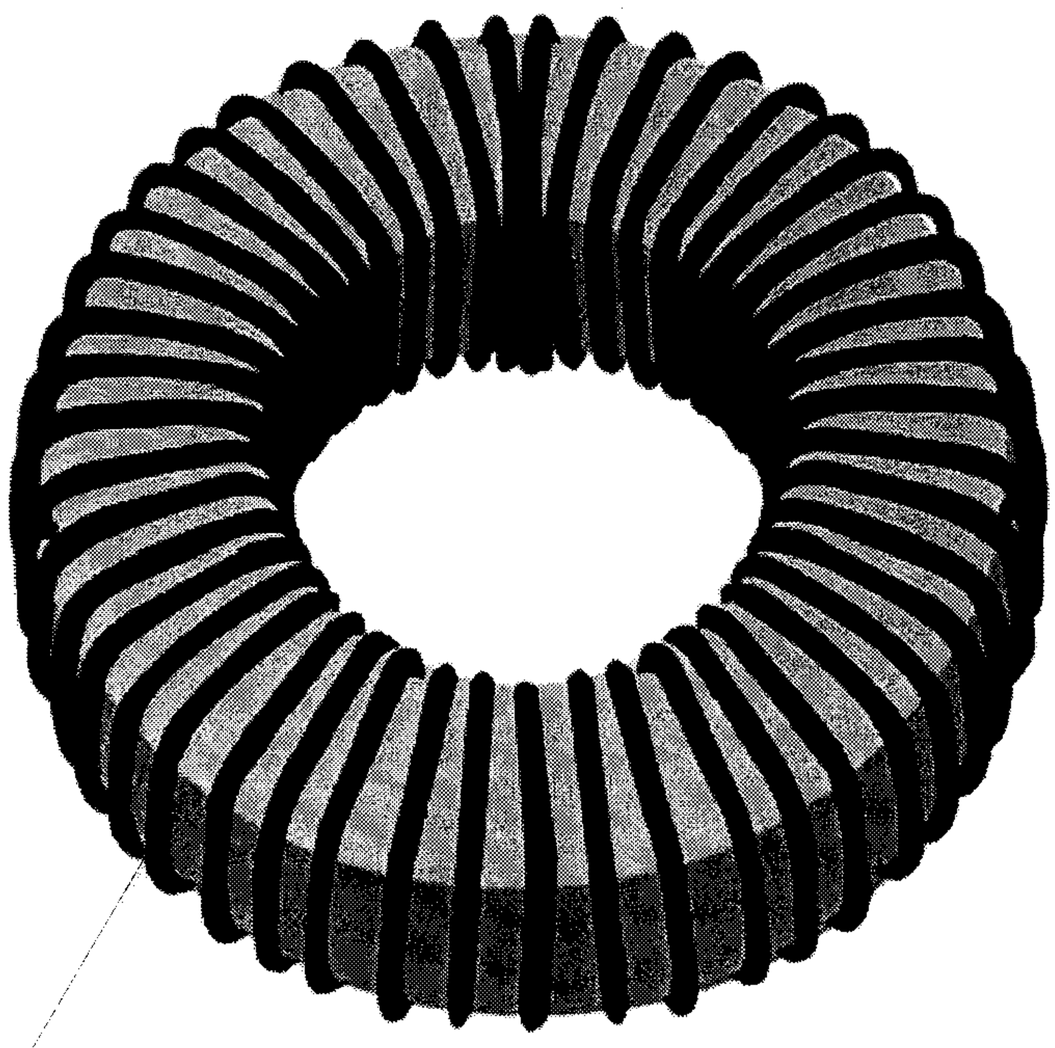



Figure 4b

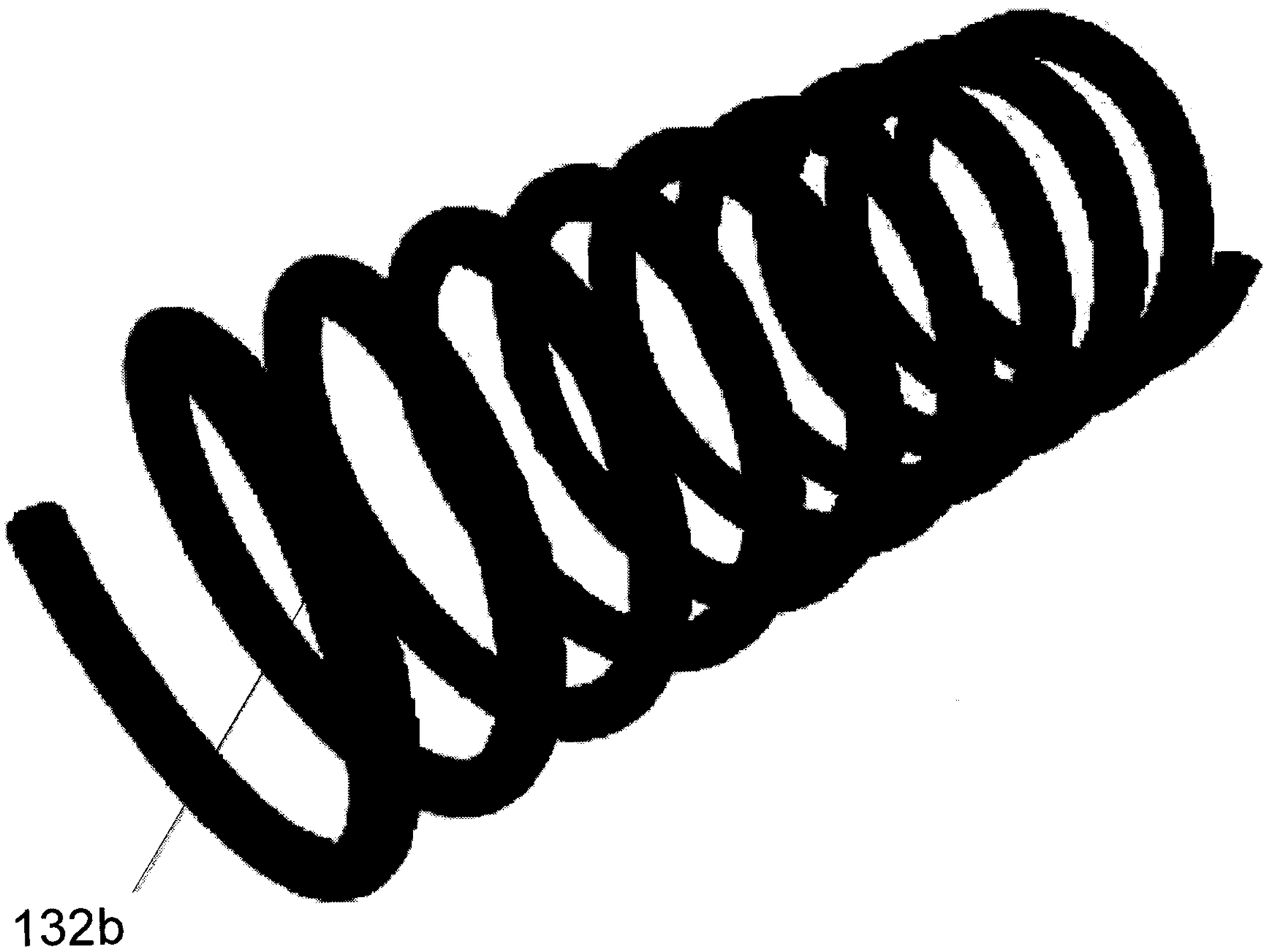



Figure 4c

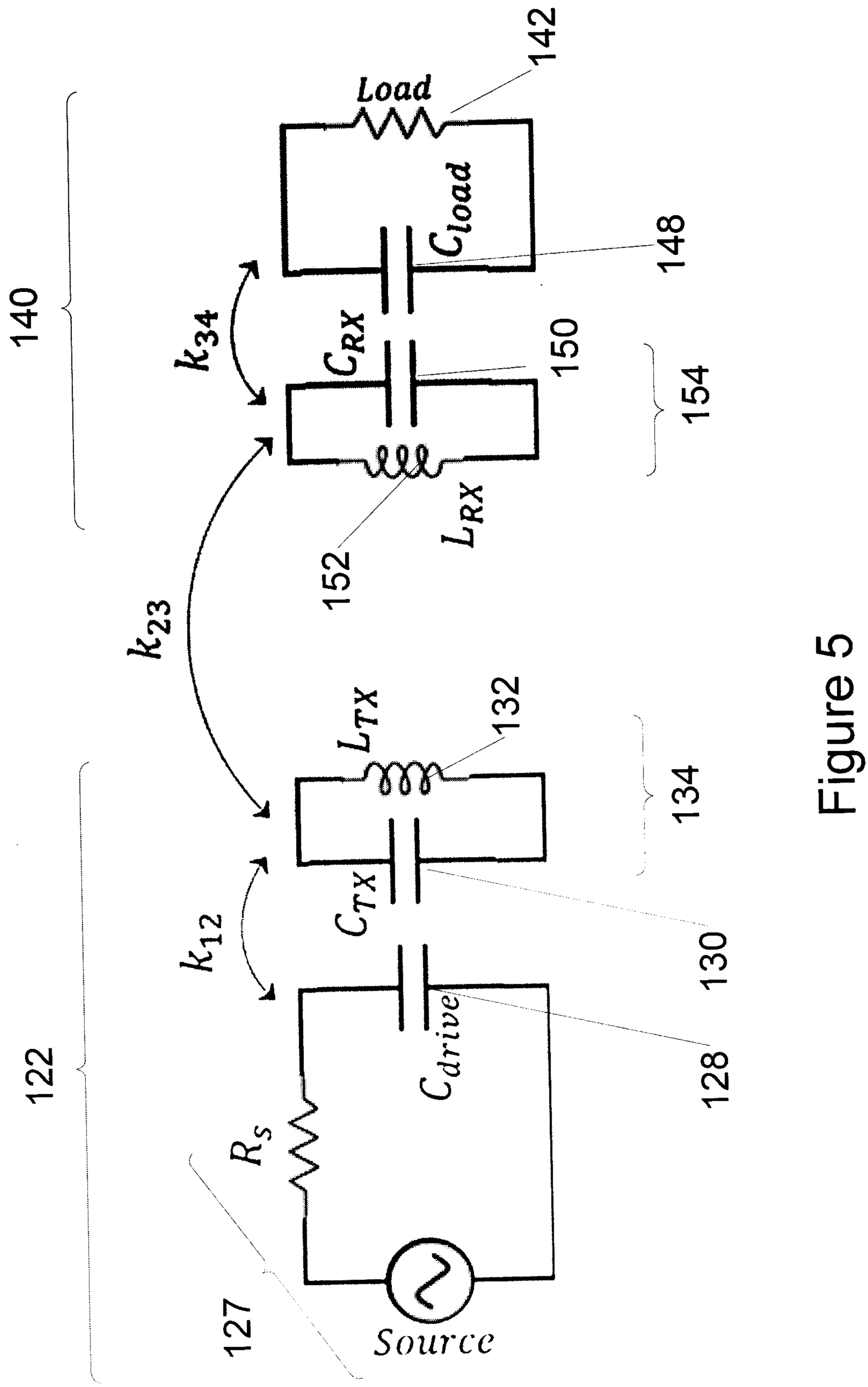

120
122
127
Source
$R_S$
$C_{drive}$
128
130
$C_{TX}$
$L_{TX}$
132
134
$k_{12}$
$k_{23}$
$k_{34}$
140
152
$L_{RX}$
$C_{RX}$
150
154
$C_{load}$
148
Load
142

Figure 5

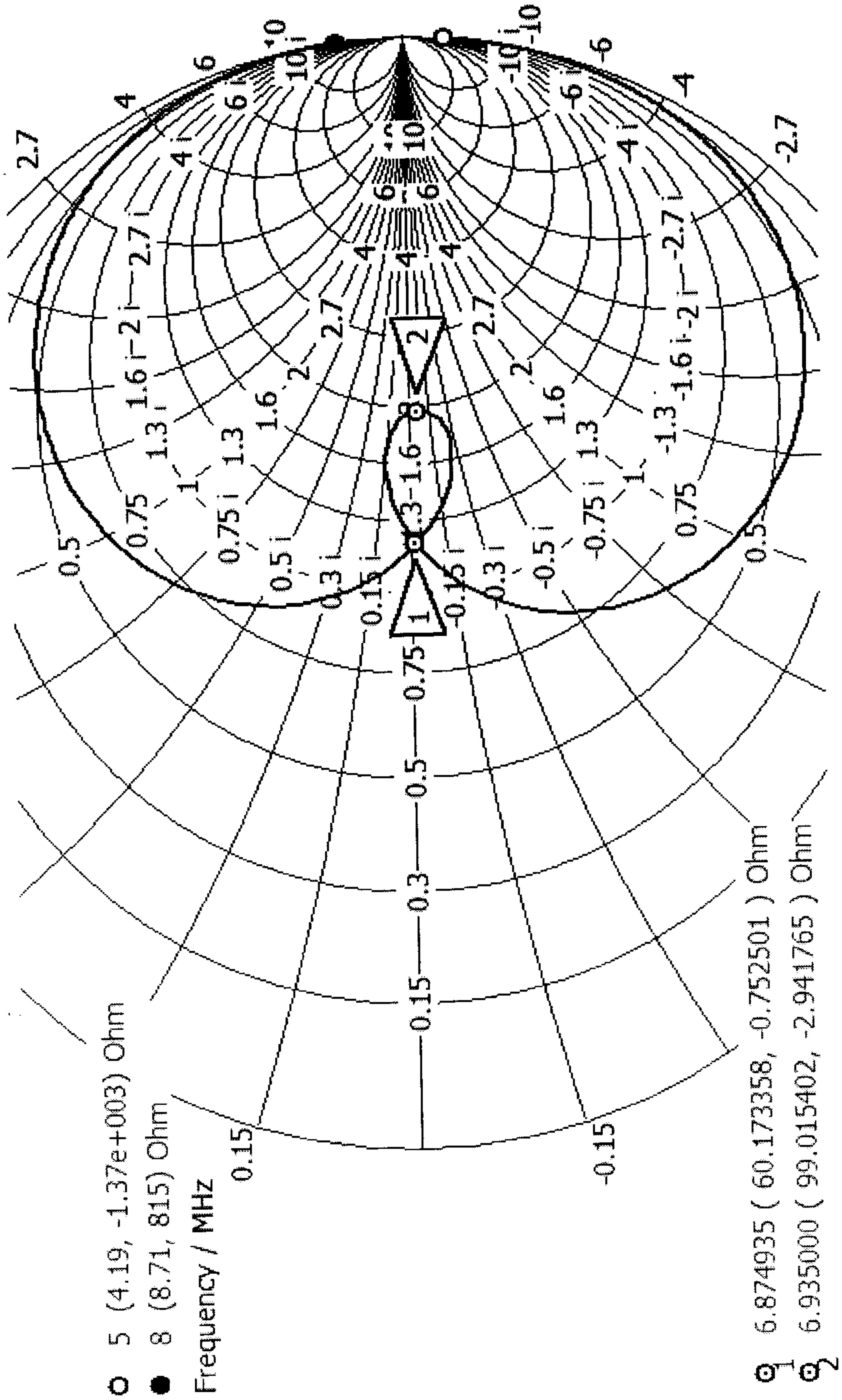

5 (4.19, -1.37e+003) Ohm
8 (8.71, 815) Ohm
Frequency / MHz
1 6.874935 ( 60.173358, -0.752501 ) Ohm
2 6.935000 ( 99.015402, -2.941765 ) Ohm

Figure 6

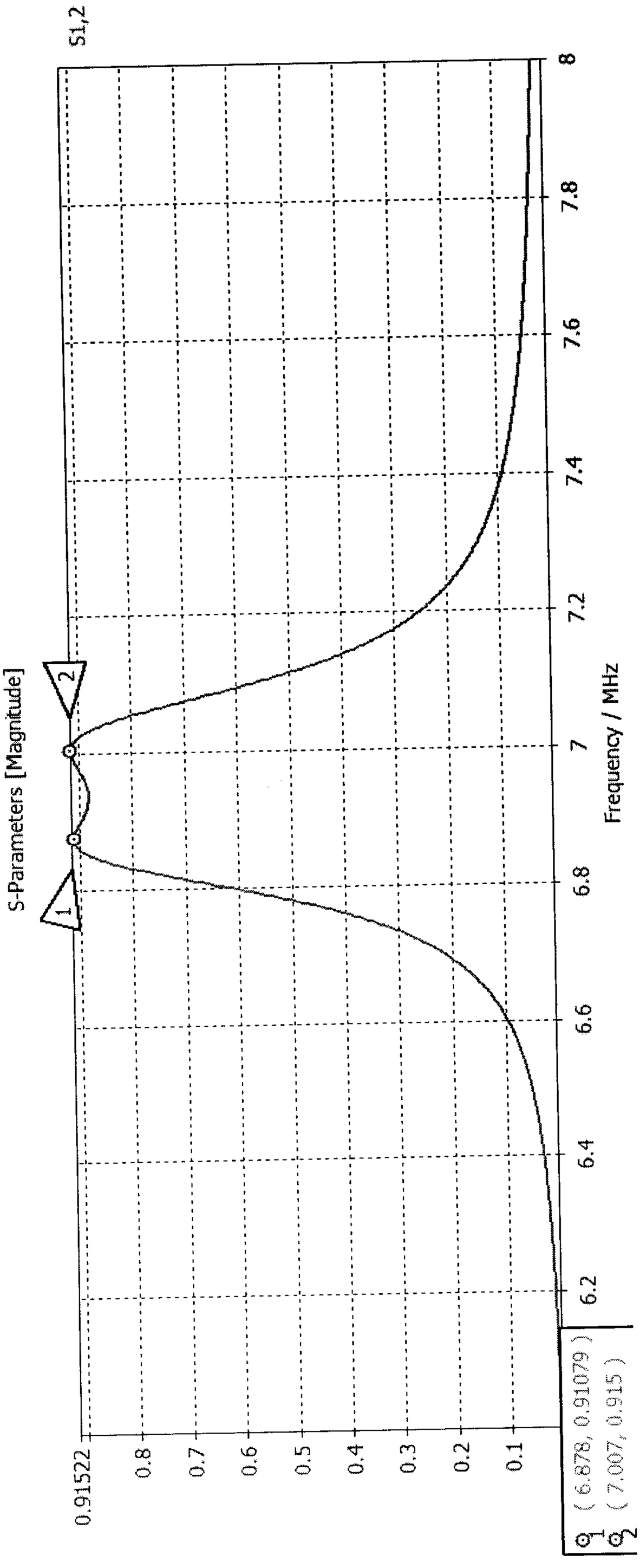

S1,2
S-Parameters [Magnitude]
Frequency / MHz
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
0.91522
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
2
( 6.878, 0.91079 )
( 7.007, 0.915 )

Figure 7

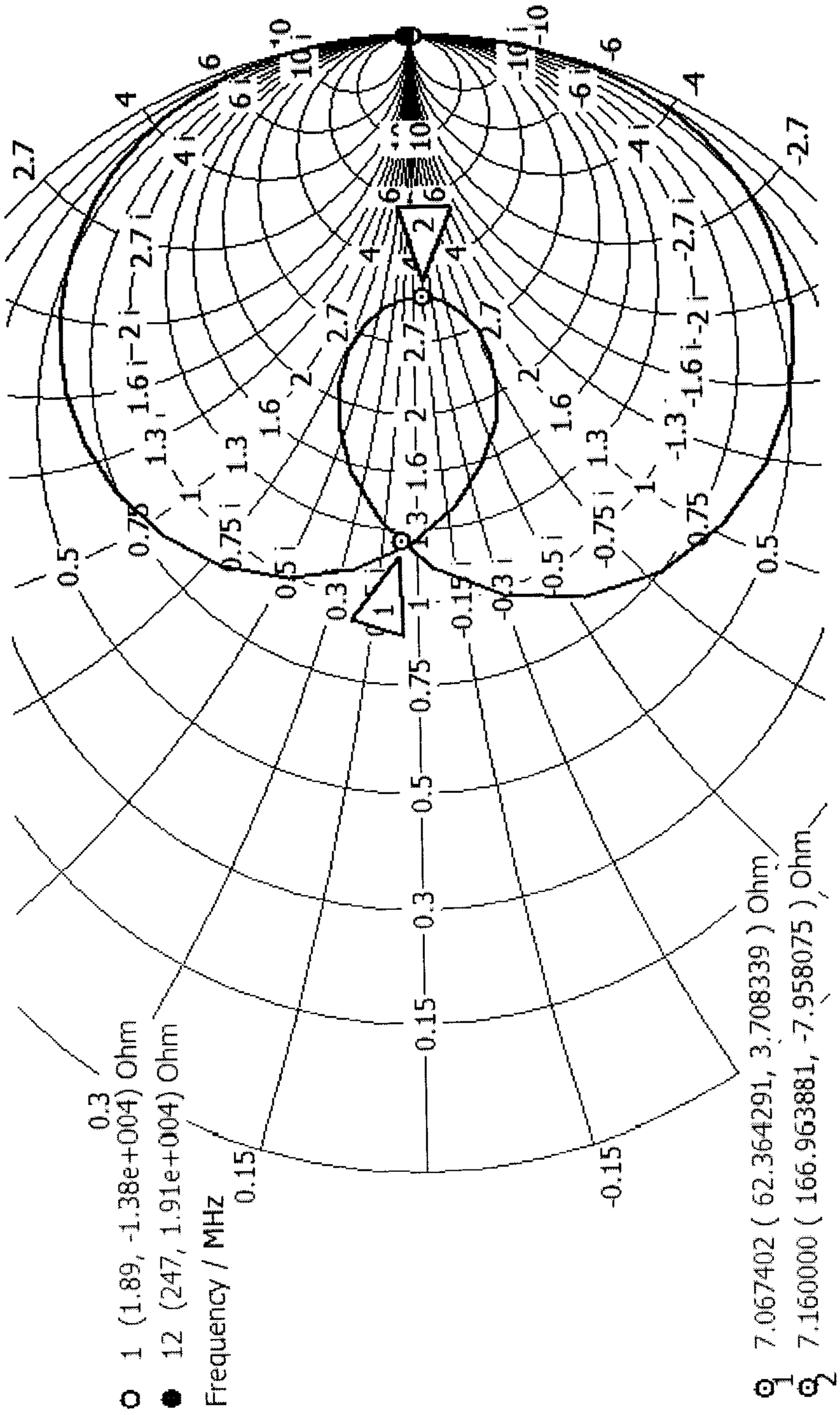

o 1 (1.89, -1.38e+004) Ohm
● 12 (247, 1.91e+004) Ohm
Frequency / MHz
o1 7.067402 ( 62.364291, 3.708339 ) Ohm
o2 7.160000 ( 166.963881, -7.958075 ) Ohm

Figure 8

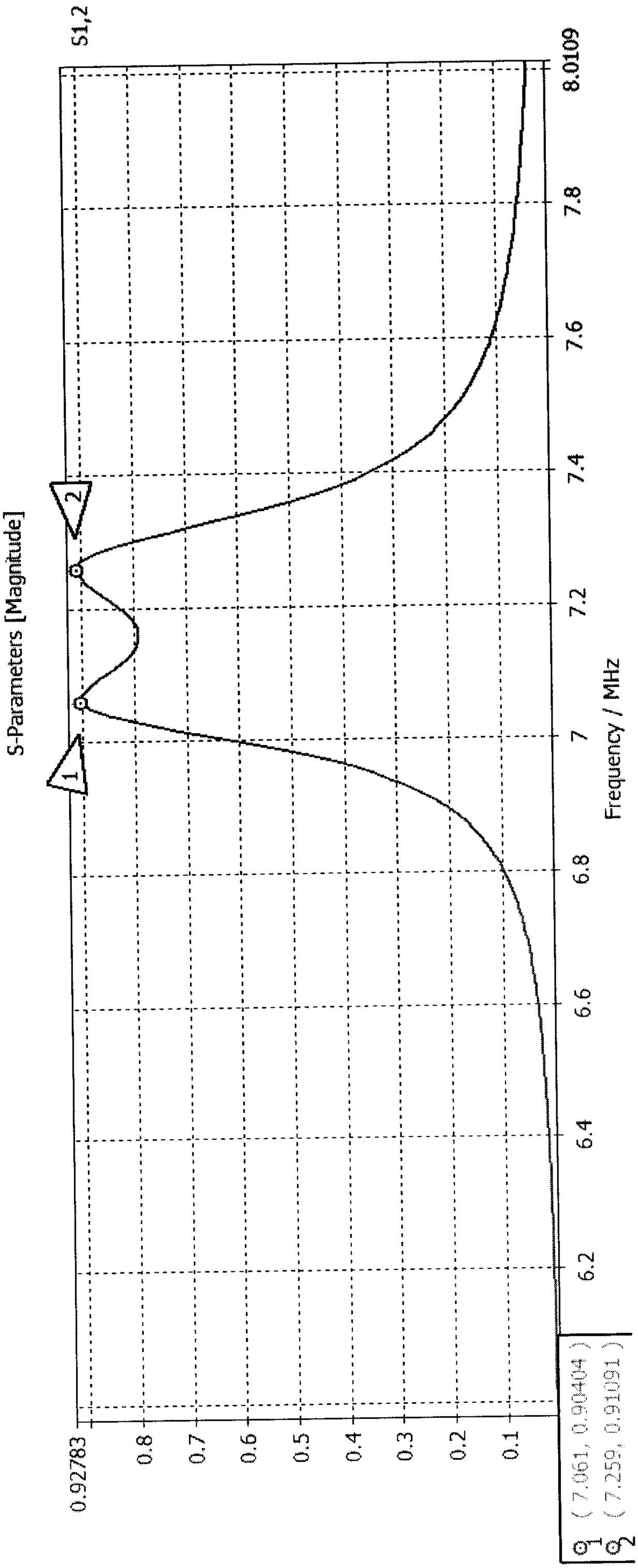

S-Parameters [Magnitude]
Frequency / MHz
51,2
0.92783
8.0109
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
2
m1 ( 7.061, 0.90404 )
m2 ( 7.259, 0.91091 )

Figure 9

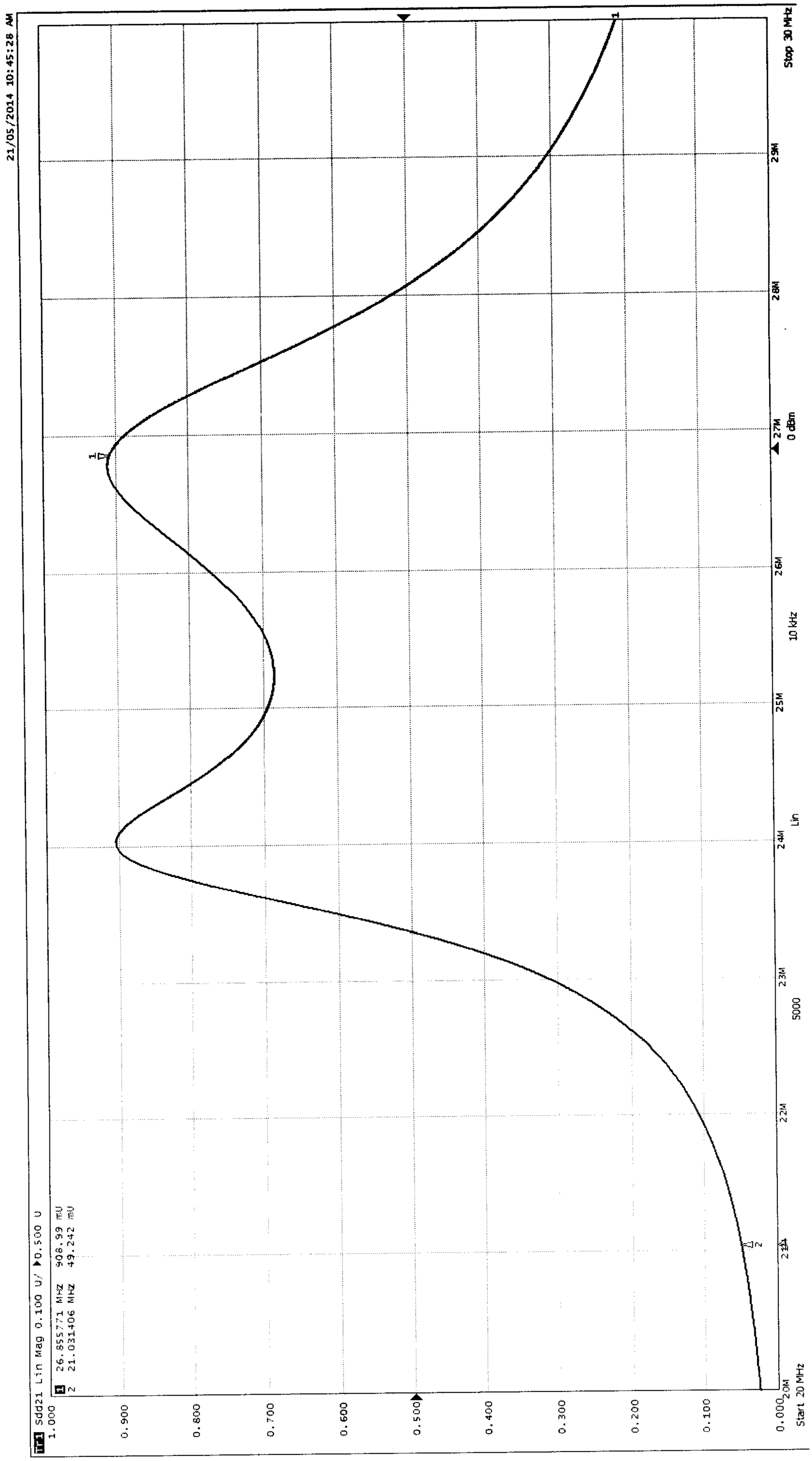

21/05/2014 10:45:28 AM
Stop 30 MHz
29M
28M
27M
0 dBm
26M
10 kHz
25M
24M
Lin
23M
5000
22M
Sdd21 Lin Mag 0.100 U/ ▶0.500 U
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
1 26.855771 MHz 908.99 mU
2 21.031406 MHz 49.242 mU
20M
Start 20 MHz

Figure 10

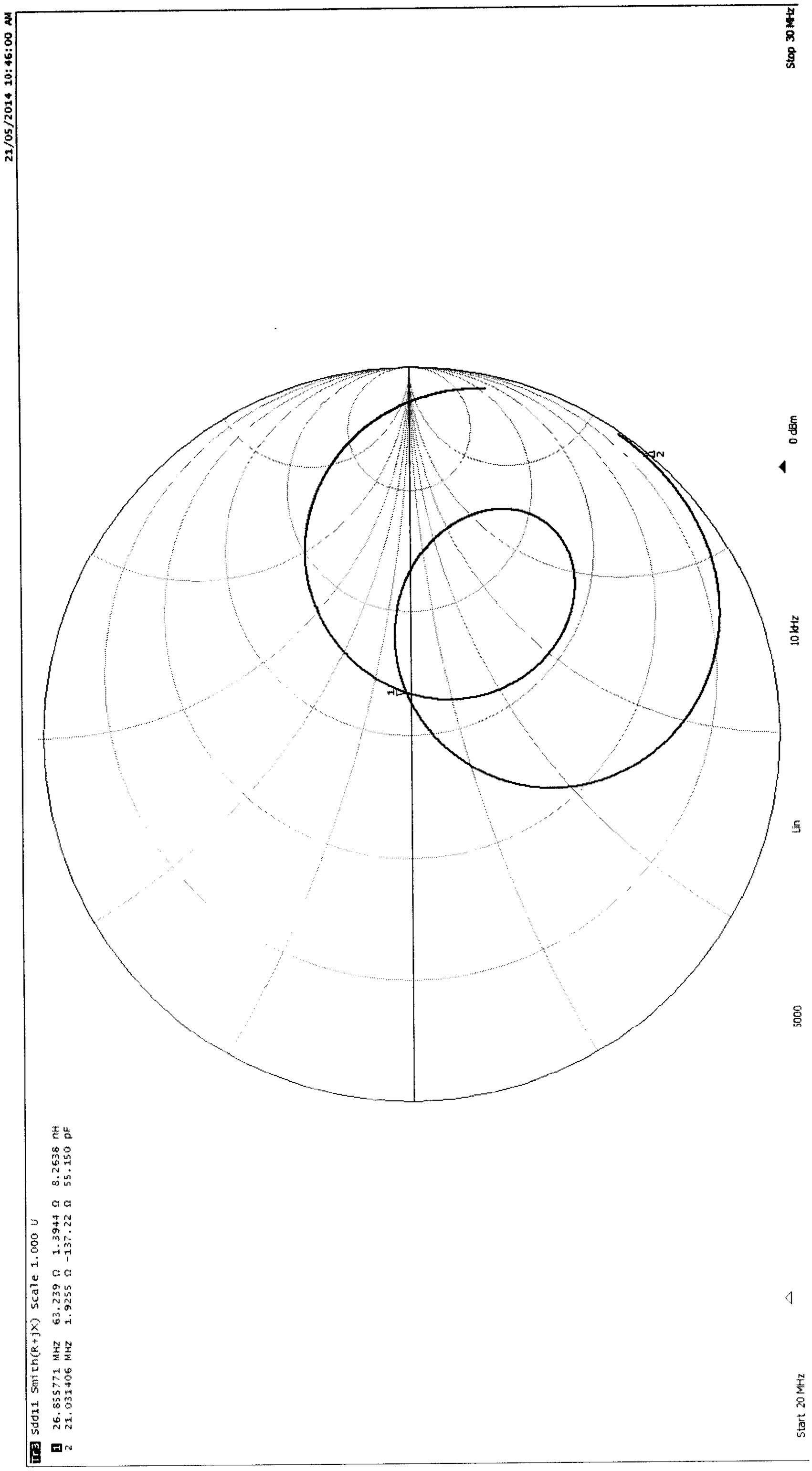

21/05/2014 10:46:00 AM
Stop 30 MHz
0 dBm
10 kHz
Lin
5000
Tr3 Sdd11 Smith(R+jX) Scale 1.000 U
1 26.855771 MHz 63.239 Ω 1.3944 Ω 8.2638 nH
2 21.031406 MHz 1.9255 Ω -137.22 Ω 55.150 pF
Start 20 MHz

Figure 11

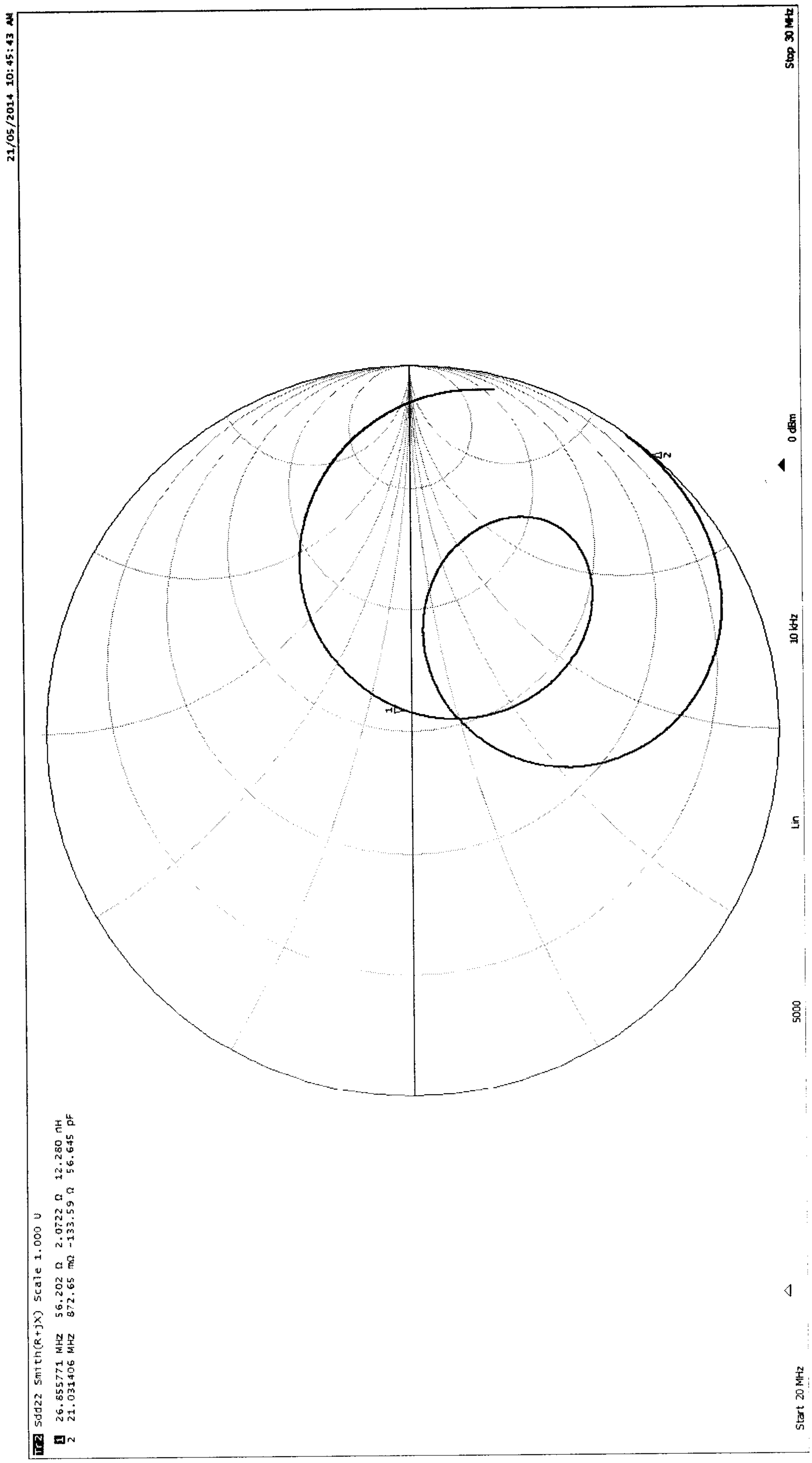

21/05/2014 10:45:43 AM
Stop 30 MHz
0 dBm
10 kHz
Lin
5000
Start 20 MHz
Tr2 Sdd22 Smith(R+jX) Scale 1.000 U
1 26.855771 MHz 56.202 Ω 2.0722 Ω 12.280 nH
2 21.031406 MHz 872.65 mΩ -133.59 Ω 56.645 pF

Figure 12

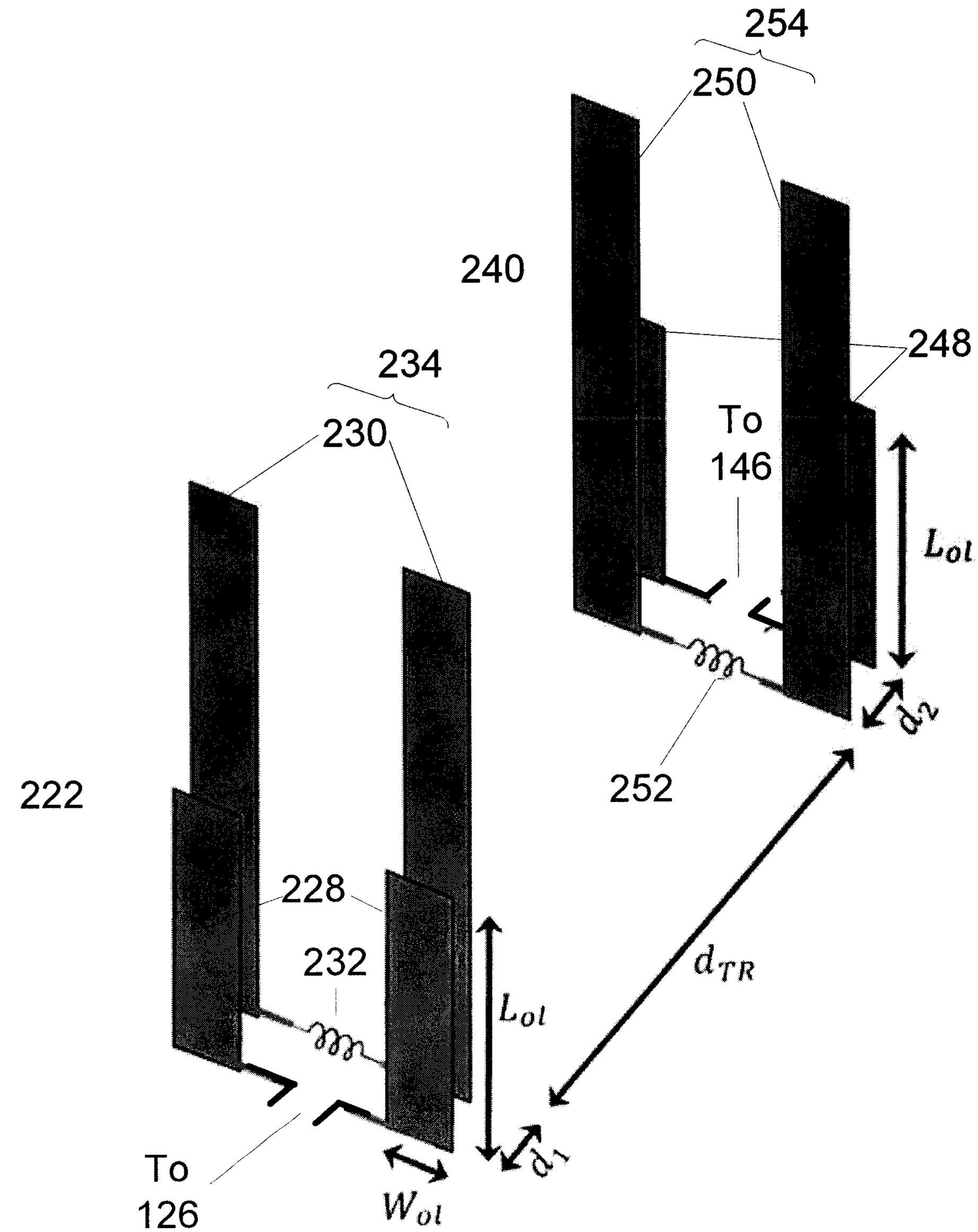

254
250
240
248
234
230
To
146
$L_{ol}$
$d_2$
252
222
228
232
$d_{TR}$
$L_{ol}$
$d_1$
To
126
$W_{ol}$

Figure 13

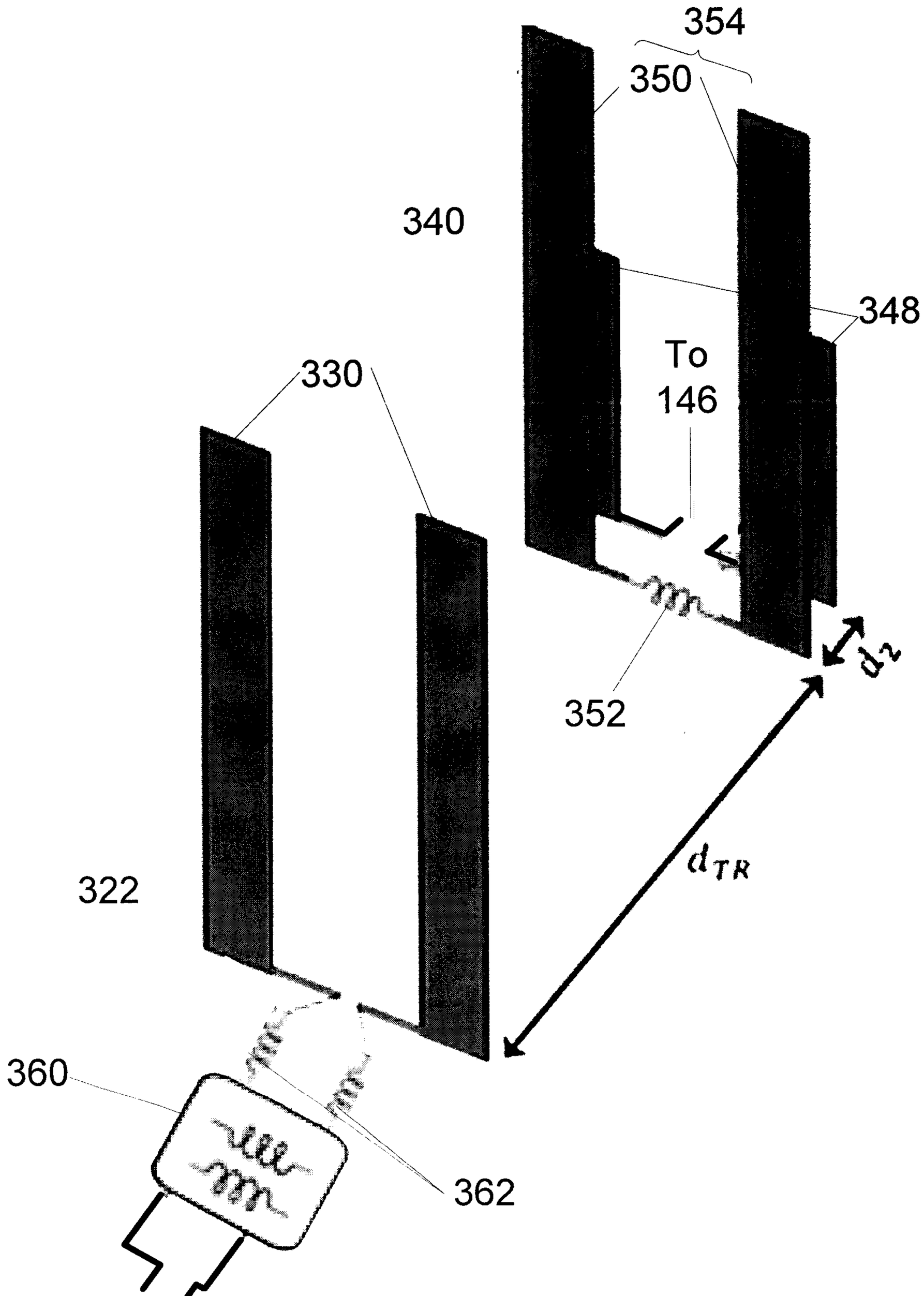



Figure 14

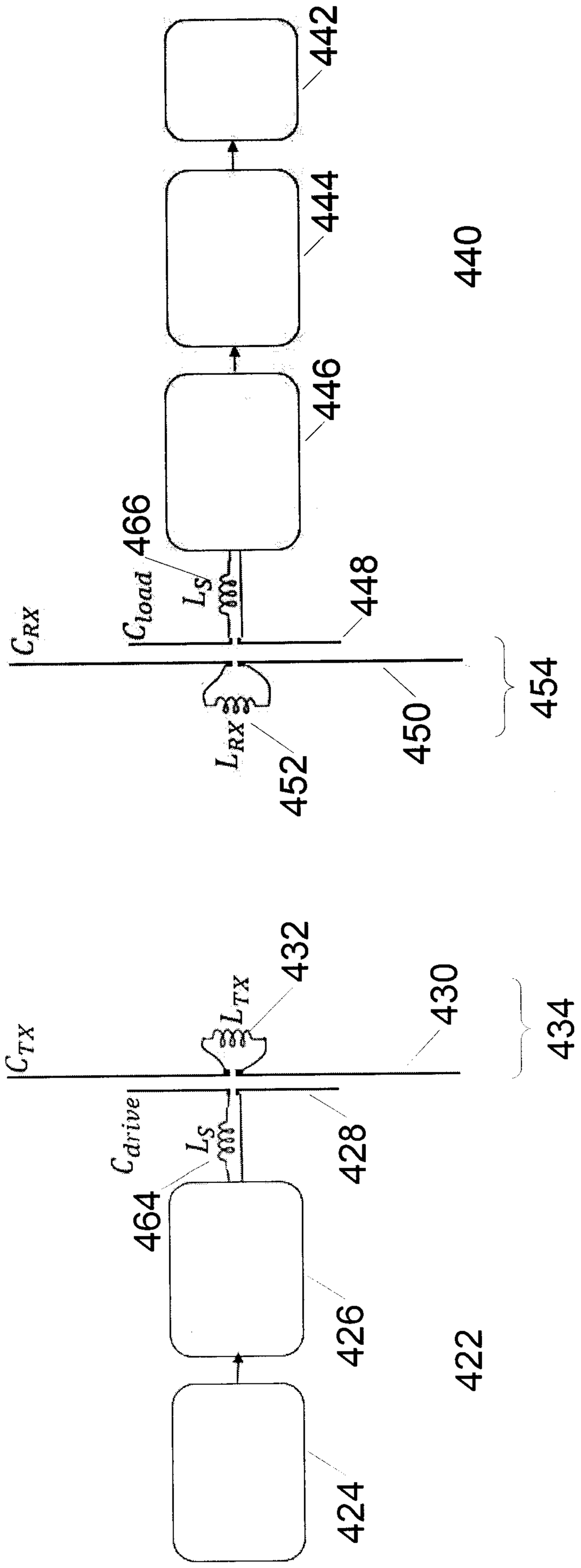

442
444
440
420
446
466
$C_{load}$
$L_S$
448
$C_{RX}$
$L_{RX}$
52
450
454
$C_{TX}$
$L_{TX}$
432
430
434
$C_{drive}$
$L_S$
464
428
426
422
424

Figure 15

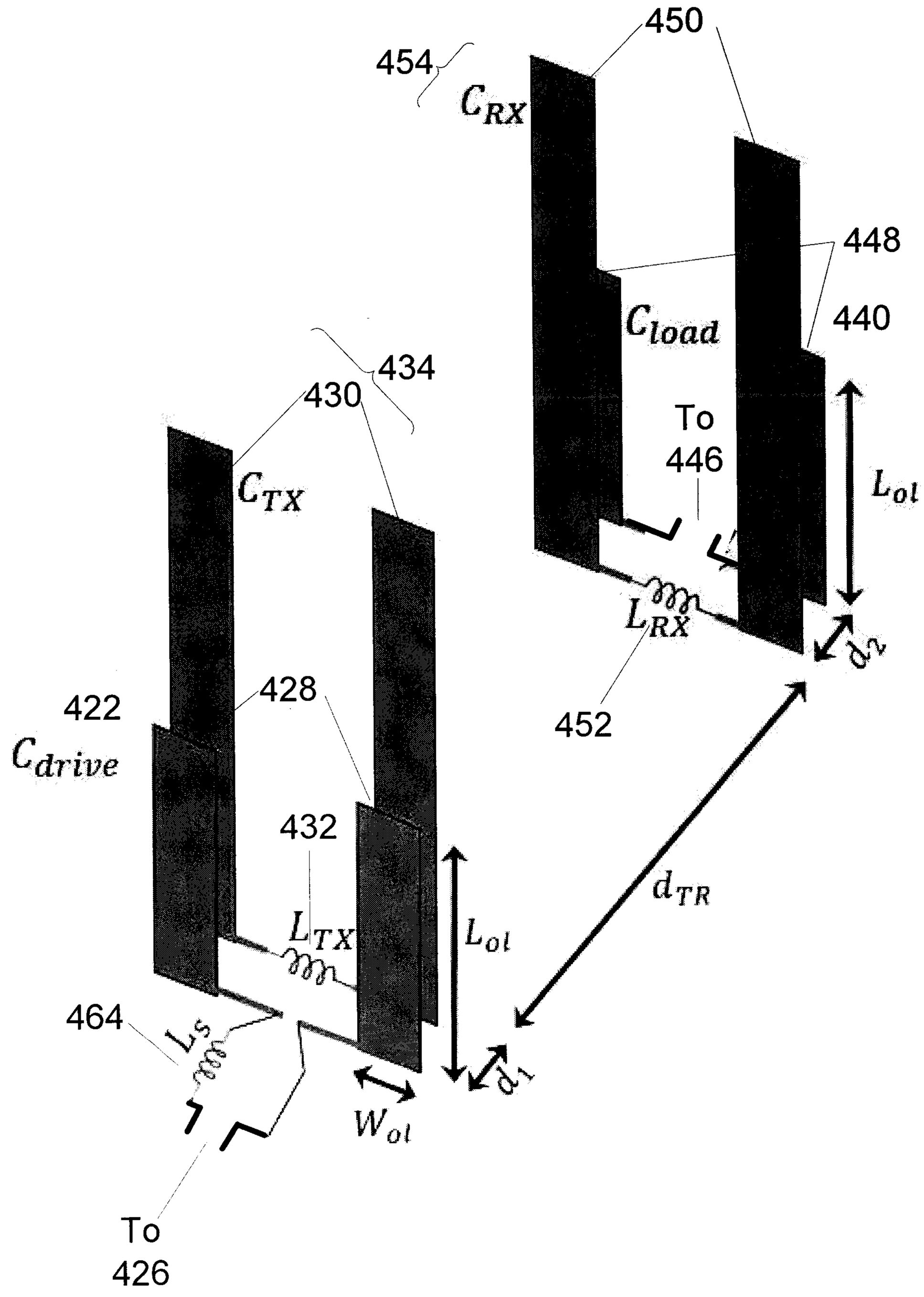

454
$C_{RX}$
450
448
440
$C_{load}$
To
446
$L_{ol}$
$L_{RX}$
$d_2$
452
434
430
$C_{TX}$
422
$C_{drive}$
428
432
$L_{TX}$
$L_{ol}$
$d_{TR}$
464
$L_S$
$W_{ol}$
$d_1$
To
426

Figure 16

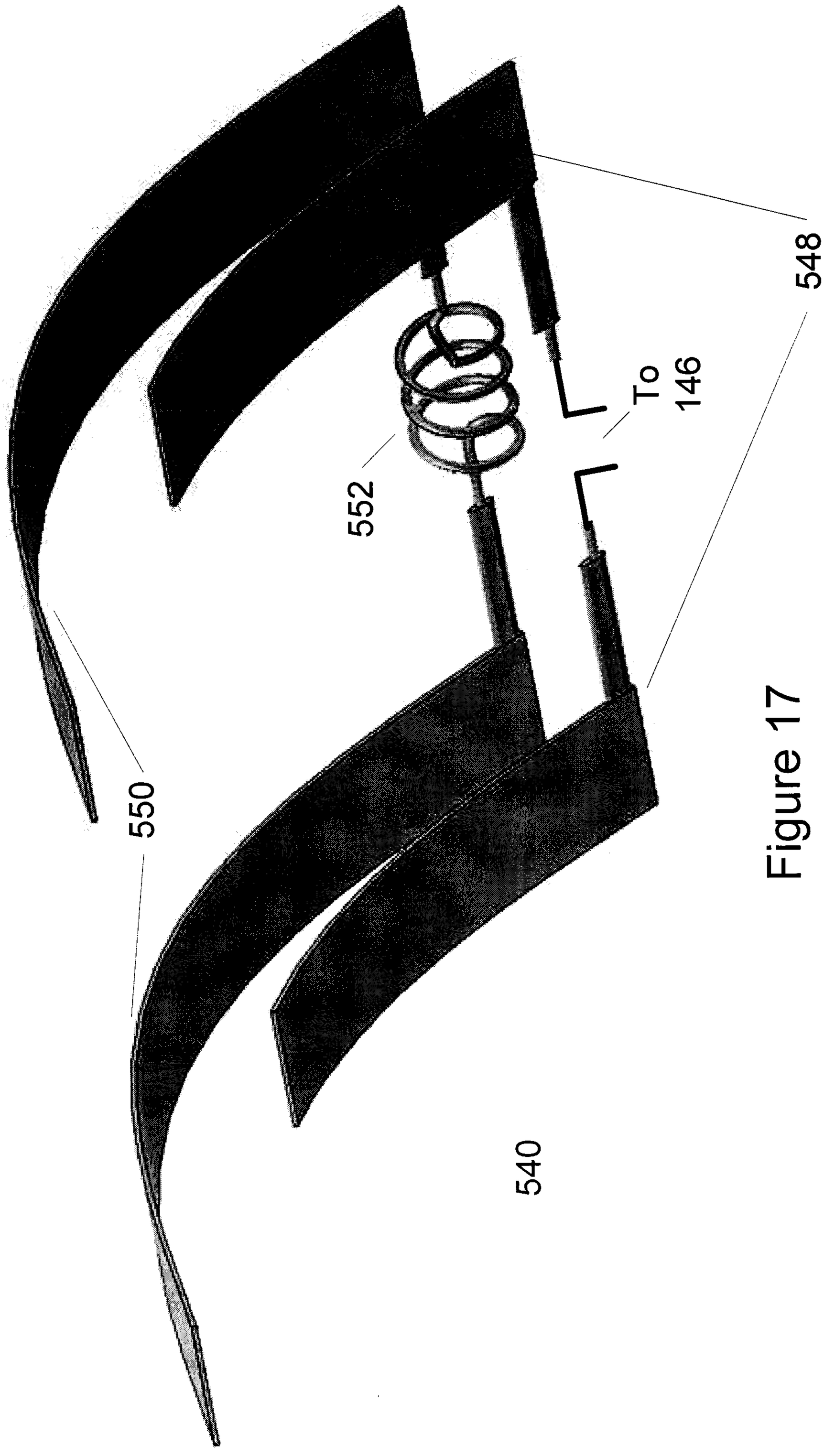



Figure 17

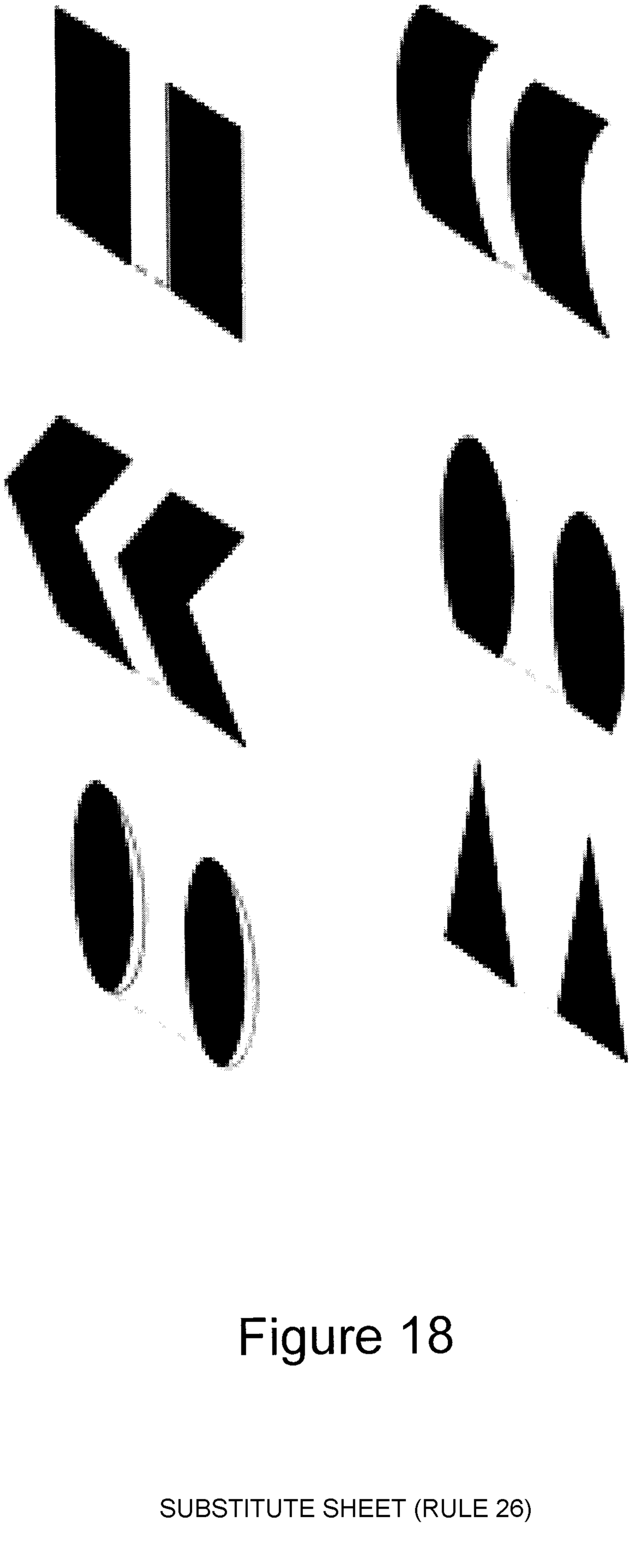


Figure 18

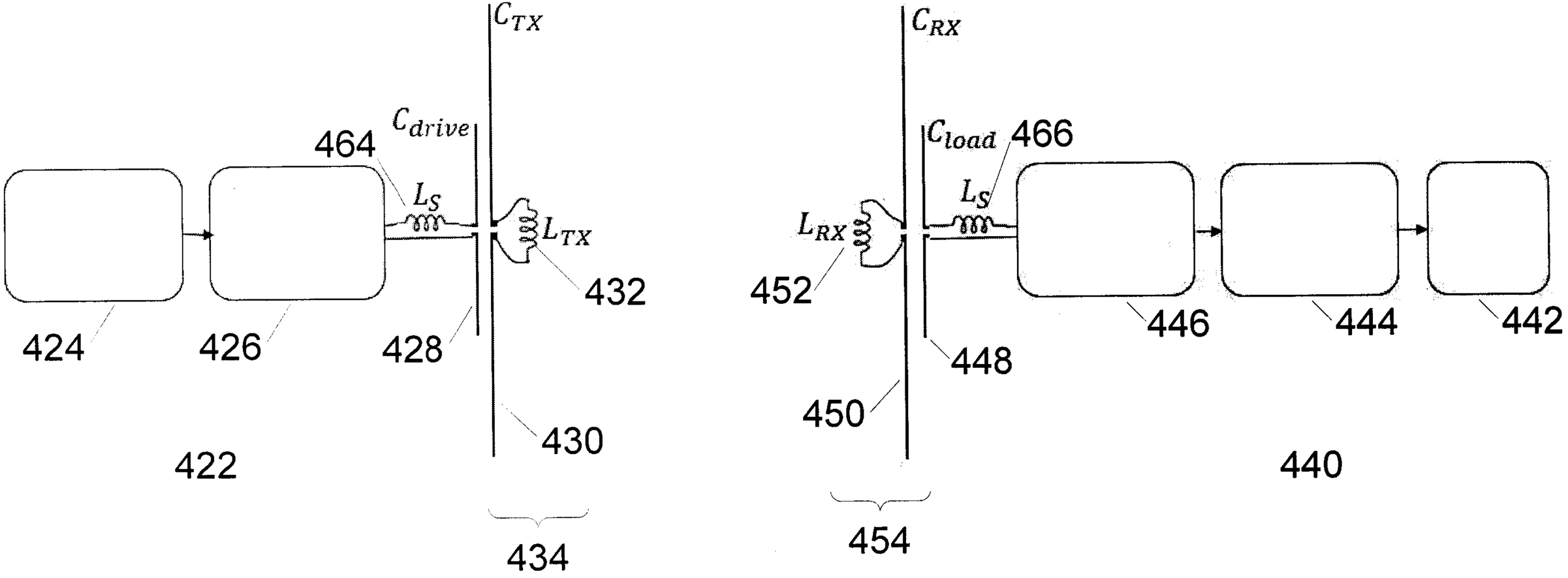

$C_{TX}$
$C_{drive}$
464
$L_S$
$L_{TX}$
432
424
426
428
430
422
434
$C_{RX}$
$C_{load}$
466
$L_S$
$L_{RX}$
452
446
444
442
448
450
440
454
420

Figure 15