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(54) **Title:** INDUCTIVELY COUPLED PULSED RF VOLTAGE MULTIPLIER

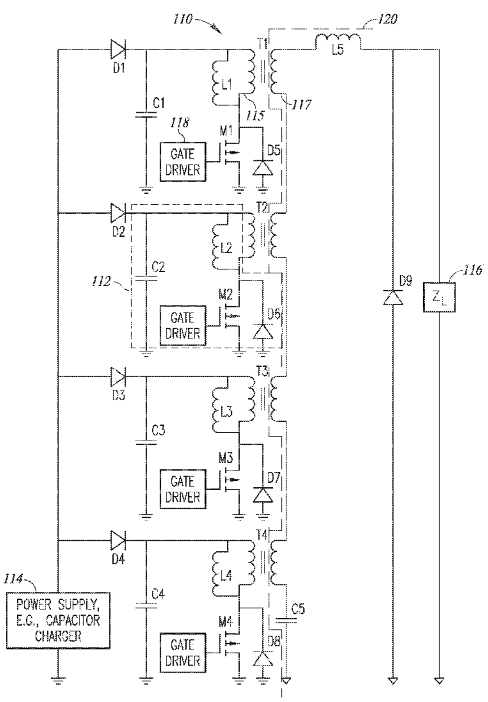

FIG. 2

(57) **Abstract:** Systems and methods for increasing the RF power switched into a resonant load by achieving voltage multiplication by means of coupled inductors are provided herein. In one approach, the RF electromagnetic wave achieved by voltage multiplication is used to drive a diode opening switch in order to create a fast rising, unipolar electrical pulse.

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INDUCTIVELY COUPLED PULSED RF VOLTAGE MULTIPLIER

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Technical Field

The present disclosure relates to systems and methods to produce high voltage, high power nanosecond pulses, which may, for example, be advantageously employed in the generation of non-thermal plasmas. More particularly, the present disclosure relates to inductively coupled pulsed radio frequency (RF) voltage multiplier circuits, and methods for generating pulsed RF waveforms.

BACKGROUND

Description of the Related Art

Pulsed radio frequency (RF) electromagnetic fields are used for numerous applications, including driving diode opening switches for the purpose of generating fast rising, unipolar pulses. One method for generating a pulsed RF electromagnetic field is to discharge a capacitor charged to a DC level into a resonant circuit. The maximum peak power of the electromagnetic wave that can be achieved is limited by the impedance of the resonant circuit and by the maximum voltage that can be held-off by the switch used to discharge the capacitor.

BRIEF SUMMARY

In order to increase the peak power and total energy of the pulsed RF discharge, a method to achieve voltage multiplication by inductive coupling has been developed. This disclosure describes electrical circuitry designed to achieve multiplication of the DC voltage that is switched into a resonant RF load.

Briefly and in general terms, the present disclosure is directed to a system for generating an RF pulse that energizes a high voltage opening switch for the purpose of producing high voltage pulses with high instantaneous power. In the various embodiments provided by the present disclosure, an inductively coupled pulsed RF voltage multiplier is used to drive a switch, such as a diode opening switch, that generates a nanosecond-scale high voltage pulse, which may be used, for example, for generating non-equilibrated plasmas and/or pulsed electric fields.

In some embodiments, the inductively coupled pulsed RF voltage multiplier circuitry is directly powered by an available DC power source, and, depending on the desired attributes of the pulse, which may vary depending on application, the DC power source may be adjustable between 0 - 1,200 VDC. In some embodiments, a large valued, high voltage resistor may be used to isolate the pulsed RF signal generated by the inductively coupled pulsed RF voltage multiplier circuitry from the DC source.

In other embodiments, capacitor charging circuitry may be used to isolate the inductively coupled pulsed RF voltage multiplier circuitry from the DC source and to provide a means to rapidly charge the input capacitance of the inductively coupled pulsed RF voltage multiplier circuitry.

As disclosed herein, the inductively coupled pulsed RF voltage multiplier switches electrical energy into a tuned resonant circuit with known impedance and natural frequency. To achieve voltage multiplication, the inductively coupled pulsed voltage multiplier includes a plurality of ground referenced switching stages, each of which is inductively coupled to the resonant circuit in a way that combines each switching stage in series. More particularly, the switching stages are electrically coupled to one another in parallel, and are inductively coupled to the tuned resonant circuit across respective transformers. The secondary windings of each of the transformers are electrically coupled in series to one another and to the resonant circuit, so that a DC charging voltage supplied to each of the switching stages is multiplied and supplied to the inductively coupled resonant circuit due to the series coupling of the secondary windings of the transformers. The input capacitance of the inductively coupled pulsed RF voltage multiplier circuitry is tuned together with the resonant load to achieve the desired impedance, natural frequency, and wave shape.

The inductively coupled pulsed RF voltage multiplier circuitry disclosed herein generally may be used to generate a high power pulse of RF energy. Depending on the design of the resonant circuit, this energy may be dissipated in a resistive load or allowed to oscillate until the energy dissipates by means of copper loss and/or dielectric loss mechanisms.

In one or more embodiments described herein, the inductively coupled pulsed RF voltage multiplier circuitry is used to drive a two-pole resonant circuit for three-quarters of one cycle of the natural frequency. Because there is a practical limit to the lowest resonant impedance that can be achieved, and, because there is a limit to the maximum voltage a given switch can hold-off, the inductively coupled pulsed RF voltage multiplier may be used to increase the amount of electrical energy that is switched into the resonant circuit. In one or more embodiments, the energy that is switched into the resonant circuit drives a diode opening switch, which is designed to interrupt the current flowing through it at a moment when the pulse energy is stored in the output inductance of the resonant circuit. The rapid interruption of current creates a high voltage pulse of nanosecond-scale duration.

In one or more embodiments, the present disclosure provides a method for generating a pulsed radio frequency (RF) waveform that includes voltage multiplying a DC charging voltage by: supplying the DC charging voltage to respective capacitors of a plurality of switching stages that are electrically coupled to one another in parallel, each of the switching stages including a switching stage capacitor, a switching stage inductor, and a switch; discharging the capacitors by concurrently switching the switches of each of the plurality of switching stages from an electrically non-conducting state to an electrically conducting state; and inductively coupling each of the plurality of switching stages to a resonant circuit through a plurality of transformers, each of the transformers having a primary winding electrically coupled to a respective switching stage and a secondary winding electrically coupled in series to one another and to the resonant circuit.

In another embodiment, the present disclosure provides a pulsed radio frequency (RF) voltage multiplier circuit that includes a plurality of switching circuits coupled to one another in parallel. Each of the switching circuits includes a switching circuit capacitor, a switching circuit inductor, and a switch. The pulsed RF voltage multiplier circuit further includes a plurality of transformers, with each of the transformers having a respective primary winding electrically coupled to a respective one of the switching circuits. A resonant circuit is inductively coupled to the plurality of switching circuits through secondary windings of each of the plurality of transformers, and the secondary windings of the plurality of transformers are electrically coupled to one another in series.

The structures, articles and methods described herein can be advantageously employed in a variety of different applications. For example, the structures, articles and methods described herein can be employed to generate pulsed power to produce a plasma, for instance a non-thermal plasma. Such can, for example, be advantageously used in applications involving pulsed power to improve efficiency of performance of combustion engines. For example, structures, articles and methods described herein may be implemented as part of, or in connection with a signal generating source that supplies pulsed power to a transient plasma circuit (e.g., via a standard ignition coil) that outputs at least one signal (e.g., an electrical pulse having a voltage and a current) that is destined to breakdown over a spark gap (e.g., the spark gap of a spark plug, a static spark gap, a rotary spark gap, and the like) at a first voltage. For example, the transient plasma circuit may be integrated into a spark plug or at any location between the signal generating source and the spark gap. The signal generating source may be integrated into the transient plasma circuit. Such can, for example, be advantageously used in applications involving pulsed power to treat textiles.

The foregoing summary does not encompass the claimed subject matter in its entirety, nor are the embodiments intended to be limiting. Rather, the embodiments are provided as mere examples.

The present disclosure addresses these and other needs.

Other features of the disclosed embodiments will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the principles of the disclosed embodiments.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

Figure 1 is a high level schematic diagram illustrating an inductively coupled pulsed RF voltage multiplier, in accordance with one or more embodiments.

Figure 2 is a schematic diagram illustrating an inductively coupled pulsed RF voltage multiplier that drives a diode opening switch that converts the RF electrical energy into a unipolar pulse generated across a load impedance, in accordance with one or more embodiments.

DETAILED DESCRIPTION

The present disclosure is generally directed to inductively coupled pulsed RF voltage multiplier circuits and methods of generating a high power RF pulse, including but not limited to the use of such circuits and methods for the purpose of generating a waveform that is suitable for driving a diode opening switch. Diode opening switches are typically designed to rapidly transition into a non-conducting reversed bias state at a time when electrical current is flowing from cathode to anode through the device. This rapid transition from a conducting to non-conducting state interrupts the current flowing from cathode to anode, and this current is diverted to a load, where it creates a fast rising electrical pulse. The voltage amplitude of the pulse is proportional to $i \times Z_L$, where I is the electrical current and Z_L is the load impedance. For a given load impedance, the amplitude of the voltage pulse is directly proportional to the value of the current, i, which in turn is proportional to the square root of the energy switched into the resonating circuit that drives the diode opening switch. Because there is a practical limit to the lowest resonant impedance that can be achieved, and, because there is a limit to the maximum voltage a given switch can hold-off, the inductively coupled pulsed RF voltage multiplier is used to increase the amount of electrical energy that is switched into the resonant circuit to achieve a higher voltage amplitude that is switched across the load impedance.

Figure 1 is a high level schematic diagram illustrating an inductively coupled pulsed RF voltage multiplier 10, in accordance with one or more embodiments. As shown in Figure 1, the inductively coupled pulsed RF voltage multiplier 10 includes a plurality of switching stages 12. Each of the switching stages 12 includes a respective switching stage capacitor $C_1 - C_4$, and a respective switch $S_1 - S_4$. The switching stages 12 are electrically coupled to one another in parallel. The switching stages 12 are further electrically coupled to primary windings 15 of respective transformers $T_1 - T_4$, as shown in Figure 1.

The capacitors $C_1 - C_4$ are charged to a DC voltage by a power supply 14, which in various implementations may be a capacitor charger or a DC voltage supply. In operation, the switches $S_1 - S_4$ are simultaneously or concurrently triggered to transition from a non-conducting state to a conducting state at some time after the capacitors $C_1 - C_4$ are suitably charged. At this time, i.e., with the switches $S_1 - S_4$ in the conducting state, the capacitors $C_1 - C_4$ begin to discharge through the primary windings 15 of the inductively coupled transformers $T_1 - T_4$. In the particular implementation shown in Figure

1, the charging voltage is multiplied by a factor of four across the resonant load 16 by virtue of the series connection between the secondary windings 17 of the inductively coupling transformers $T_1 - T_4$. The switched energy resonates in the tuned RF load 16, creating a high voltage RF pulse.

Figure 2 is a schematic diagram illustrating an inductively coupled pulsed RF voltage multiplier 110 that drives a diode opening switch D9 that converts the RF electrical energy into a unipolar pulse generated across a load impedance 116, in accordance with one or more embodiments. As shown in Figure 2, the inductively coupled pulsed RF voltage multiplier 110 may be coupled to a power supply 114, such as a capacitor charger, and diodes $D_1 - D_4$ that isolate the power supply 114 from the inductively coupled pulsed RF voltage multiplier 110 circuitry. The inductively coupled pulsed RF voltage multiplier 110 may include a plurality of capacitors $C_1 - C_4$ that are charged by the capacitor charger, a plurality of switches, such as MOSFETs $M_1 - M_4$ with anti-parallel diodes $D_5 - D_8$ to switch the capacitors $C_1 - C_4$ into the resonating RF circuit, transformers $T_1 - T_4$ to provide the inductive coupling and voltage multiplication, inductors $L_1 - L_5$ and an additional capacitor C_5 to form the resonant circuit, and a diode opening switch D_9 to form a high voltage nanosecond-scale pulse that may be applied to a load Z_L that absorbs the nanosecond-scale pulse. The nanosecond-scale pulse may be a pulse having a length of equal to or less than 100 nanoseconds at the full-width-at-half-maximum (FHWM) and an amplitude of at least 1 kV. In one or more embodiments, the nanosecond-scale pulse may have a length within a range of 10 nanoseconds, inclusive, to 10 nanoseconds, inclusive, at the FHWM. In one or more embodiments, the pulse may have an amplitude within a range of 10kV, inclusive, to 40kV, inclusive. In some embodiments, the pulse has an amplitude that is greater than 40kV.

Figure 2 depicts a configuration in which four switching stages 112 are inductively coupled by transformers $T_1 - T_4$ to provide a voltage multiplication factor of 4, meaning that the voltage that is switched across the series combination of the inductor L_5 and the diode opening switch D_9 is four times higher than the charge voltage provided by the power supply 114, which may be a capacitor charger. In general, the number of switching stages 112 may be as many as desired depending on application, from 1 up to N stages, where N is the number of switching stages 112 required to achieve the desired output voltage. Each of the switching stages 112 includes a respective switching stage capacitor $C_1 - C_4$, a respective switching stage inductor $L_1 - L_4$, and a respective switch, such as MOSFETs $M_1 - M_4$. Each of the switching stages 112 thus includes respective LC or resonant switching stage circuits that include the respective switching stage capacitors and the switching stage inductors. The switching stages 112 are electrically coupled to one another in parallel. The switching stages 112 are further electrically coupled to primary windings 115 of respective transformers $T_1 - T_4$, as shown in Figure 2. The secondary windings 117 of the transformers $T_1 - T_4$ are coupled in series to one another and to a resonant circuit 120 that includes the inductor L_5 and the capacitor C_5. The secondary windings 117 of the transformers $T_1 - T_4$ may be included as part of the resonant circuit 120.

As shown in Figure 2, the capacitors $C_1 - C_4$ may be switched into the resonant circuit 120by the MOSFETs $M_1 - M_4$. The MOSFETs $M_1 - M_4$ may preferably be used as a switching element in one or more embodiments due to their fast turn-on time; however, other switches may be used, including, but not limited to, insulated gate bipolar transistors (IGBTs), thyristors, silicon controlled thyristors, bipolar junction transistors, other field effect transistors, thyratrons, spark gap switches, photoconductive solid state switches, or any solid state, avalanche, optically triggered or gas discharge switches. Depending on the switching technology used, anti-parallel diodes $D_5 - D_8$ may be employed in the switching stages 112 to provide a reverse conduction path across the switch, though they may not be included, for example, if the switching technology employed is capable of conducting in the reverse direction. In practice, the chosen switching technology should feature a turn-on time that is a fraction of one-quarter of the resonant period of the resonant circuit 120 to avoid excessive switching loss.

Each of the switches (e.g., MOSFETs $M_1 - M_4$) of the switching stages 112 may include a plurality of switching elements that are electrically coupled to one another in parallel, series, or series-parallel in order to increase an effective voltage and a current rating of each of the switches.

In operation, MOSFETs $M_1 - M_4$ are simultaneously or concurrently triggered to conduct electrical current at some time after capacitors $C_1 - C_4$ are fully or otherwise suitably charged by the power supply 114, e.g., the capacitor charger. The MOSFETs $M_1 - M_4$ may be controlled by any control circuit, such as by one or more gate driver circuits 118 that selectively control the MOSFETs $M_1 - M_4$ to operate in conductive and non-conductive states. When the MOSFETs $M_1 - M_4$ are trigged to operate in their conductive states, the switching stage inductors $L_1 - L_4$ are connected in parallel across the switching stage capacitors $C_1 - C_4$, respectively, forming a plurality of switching stage resonant circuits, each including a respective switching stage inductor $L_1 - L_4$ and a respective switching stage capacitor $C_1 - C_4$. The impedance of these parallel resonant switching stage circuits appears on the secondary side of transformers $T_1 - T_4$ across the series combination of the inductor L_5 and the diode opening switch D_9 as an equivalent parallel tank circuit with an equivalent capacitance of $1/C_{eq} = 1/C_1 + 1/C_2 + 1/C_3 + 1/C_4$ and an equivalent inductance of $L_{eq} = L_1 + L_2 + L_3 + L_4$. In general, when N switching stages are used, the equivalent capacitance and inductance is given by $1/C_{eq} = 1/C_1 + 1/C_2 + \ldots + 1/C_{N-1} + 1/C_N$ and $L_{eq} = L_1 + L_2 + \ldots + L_{N-1} + L_N$. This equivalent parallel tank circuit resonates in conjunction with the resonant circuit 120 including the capacitor C_5 and the inductor L_5 to pump the diode opening switch D_9.

When the MOSFETs $M_1 - M_4$ are concurrently switched from electrically non-conductive state into electrically conductive states, the electrical energy that is initially stored in the switching stage capacitors $C_1 - C_4$ as a uniform DC voltage is converted to a radio frequency (RF) voltage. The switching stage capacitors $C_1 - C_4$ discharge the stored electrical energy into the inductively coupled resonant circuit 120 to achieve an effective switching voltage that is higher than the DC charging voltage by a multiplying factor. The multiplying factor is dependent on the number of switching stages 112, and in the example shown in Figure 2, the multiplying factor is four.

In the preferred implementation, inductive coupling between the switching stages 112 and the resonant circuit 120 is achieved by the transformers $T_1 - T_N$, where N is the number of switching stages 112. As shown in Figure 2, the inductively coupled pulsed RF voltage multiplier 110 may include four transformers; however, fewer or more transformers may be included. To achieve a high degree of inductive coupling, transformers having toroidal magnetic cores with high magnetic permeability may be used in one or more embodiments, though in other embodiments the inductive coupling may be achieved generally by any structure with a mutual inductance between two conductors. Such structures may or may not use magnetic materials to increase the magnetic susceptibility of the medium that couples the magnetic fields to create a mutual inductance. In general, the primary and secondary conductors that form the transformer may be wound in an aircore configuration, or wound on or around a magnetic material, such as nanocrystalline ribbon, ferrite, iron powder, and other crystalline or amorphous magnetic materials. In implementations in which the transformers are aircore transformers, the magnetizing inductance of the aircore transformers may be sufficiently small to resonate as part of the overall pulsed RF circuitry, creating a resonantly tuned, inductively coupled pulsed RF voltage multiplier.

In one or more implementations, the transformers $T_1 - T_N$ have a same number of turns on the primary winding 115 and the secondary winding 117 to achieve a 1:1 transformation ratio. In such implementations, electrical energy is switched into the primary winding 115 of each transformer, which is referenced to a common equipotential, and the secondary winding 117 of each transformer is connected in series to the secondary winding 117 of the neighboring transformers. Accordingly, the overall voltage multiplication provided is given by N, where N is the number of transformers and the number of switching stages 112 included in the inductively coupled pulsed RF voltage multiplier 110.

In one or more implementations, the transformers $T_1 - T_N$ have an unequal number of turns on the primary winding 115 and the secondary winding 117 to achieve a 1:n transformation ratio. In such embodiments, electrical energy is switched into the primary winding 115 of each transformer, which is referenced to a common equipotential, and the secondary winding 117 of each transformer is connected in series to the secondary winding of the neighboring transformers. Accordingly, the overall voltage multiplication provided is given by $n \times N$, where n is the turns ratio of the transformers and N is the number of transformers.

The transformers $T_1 - T_N$ may by designed such that the non-coupled magnetic field on the secondary side of the transformers may form an effective leakage inductance that is equal to or less than the desired value of the inductor L_5. In the case that the effective leakage inductance is equal to the desired value of the inductor L_5, the inductor L_5 may be eliminated from the circuit, as the inductance is part of the transformers themselves.

The dynamic behavior of the pulsed RF energy and the peak value of the oscillating current is determined based on the arrangement and values of the inductance and capacitance in the inductively coupled pulsed RF voltage multiplier 110 circuitry. In various embodiments, the pulsed RF circuitry is used to drive a diode opening switch. In various embodiments, a practical range for the natural frequency of resonating inductance and capacitance is between 100 kHz and 10 MHz. The impedance of the resonant circuit can be chosen by a user or circuit designer as desired, depending on application. In one or more embodiments, the overall equivalent impedance of the resonant circuit may be between 1 Ω and 1,000 Ω.

The resonant circuit, e.g., the resonant circuit 120 on the secondary winding side of the transformers, may include various discrete passive components, including inductors, capacitors, and resistors, all of which may be selected and arranged in the circuit as desired to obtain the desired dynamics and instantaneous power of the pulsed RF energy.

In one or more embodiments, the diode opening switch D_9 includes an array of diode opening switches.

The various embodiments and examples described above are provided by way of illustration only and should not be construed to limit the claimed invention, nor the scope of the various embodiments and examples. Those skilled in the art will readily recognize various modifications and changes that may be made to the claimed invention without following the example embodiments and applications illustrated and described herein, and without departing from the true spirit and scope of the claimed invention, which is set forth in the following claims.

Various structures, articles, and methods described herein may be advantageously employed in specific applications or with other structures, articles, and methods, such as those described in U.S. Provisional Patent Application No. 61/717,044, filed October 22, 2012; U.S. Non-Provisional Patent Application No. 14/052,437, filed October 11, 2013 (published as US 2014/0109886); U.S. Provisional Patent Application No. 61/916,693 filed December 16, 2013; U.S. Non-Provisional Patent Application No. 14/571,128 filed December 15, 2014 (granted as U.S. 9,617,965); U.S. Non-Provisional Patent Application No. 15/444,112, filed February 27, 2017 (published as US 2017/0167464); and U.S. Provisional Patent Application No. 62/620278, filed January 22, 2018, each of which is incorporated herein by reference in their entireties.

The various embodiments described above can be combined to provide further embodiments. These and other changes can be made to the embodiments in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

CLAIMS

1. A method for generating a pulsed radio frequency (RF) waveform, comprising:

voltage multiplying a DC charging voltage by:

supplying the DC charging voltage to respective capacitors of a plurality of switching stages that are electrically coupled to one another in parallel, each of the switching stages including a switching stage capacitor, a switching stage inductor, and a switch; and

discharging the capacitors by concurrently switching the switches of each of the plurality of switching stages from an electrically non-conducting state to an electrically conducting state; and

inductively coupling each of the plurality of switching stages to a resonant circuit through a plurality of transformers, each of the transformers having a primary winding electrically coupled to a respective switching stage and a secondary winding electrically coupled in series to one another and to the resonant circuit.

2. The method of claim 1 wherein the resonant circuit includes an inductor and a capacitor electrically coupled in series to the secondary windings of the transformers.

3. The method of claim 1 wherein each of the transformers have a same number of turns on the primary winding and the secondary winding to achieve a 1:1 transformation ratio.

4. The method of claim 1 wherein each of the transformers have an unequal number of turns on the primary winding and the secondary winding to achieve a 1:n transformation ratio.

5. The method of claim 1 wherein each of the transformers includes two or more windings on a magnetic material.

6. The method of claim 5 wherein the magnetic material includes at least one of: nanocrystalline ribbon, ferrite, iron powder, crystalline magnetic material, and amorphous magnetic material.

7. The method of claim 1wherein the transformers are air core transformers and each transformer includes two or more windings on a non-magnetic structure.

8. The method of claim 1 wherein the resonant circuit includes a leakage inductance due to uncoupled magnetic fields of the secondary windings of the transformers, and a value of the leakage inductance is tuned with the resonant circuit.

9. The method of claim 1, further comprising: converting the DC charging voltage from a uniform DC voltage stored in the switching stage capacitors to a radio frequency (RF) voltage by the concurrently switching the switches of each of the plurality of switching stages from the electrically non-conducting state to the electrically conducting state.

10. The method of claim 1 wherein each of the switches of the switching stages includes a plurality of switching elements electrically coupled to one another in parallel, series, or series-parallel to increase an effective voltage and a current rating of each of the switches.

11. The method of claim 1 wherein the switches include at least one of: field effect transistors, insulated gate bipolar transistors, thyristors, silicon controlled

thyristors, bipolar junction transistors, photo conductive solid state switches, thyratrons, spark gaps, or any solid state, avalanche, optically triggered or gas discharge switches.

12. The method of claim 1, further comprising:

generating a pulsed RF waveform by the inductively coupling each of the plurality of switching stages to the resonant circuit through the plurality of transformers; and

driving an opening switch with the pulsed RF waveform to convert RF energy of the pulsed RF waveform into a unipolar pulse.

13. The method of claim 12 wherein the opening switch includes at least one of a diode or an array of diodes.

14. The method of claim 12 wherein a natural frequency of the pulsed RF waveform that drives the diode opening switch is between 100 kHz, inclusive, and 10 MHz, inclusive, and an equivalent resonant impedance of the resonant circuit is between 0.1 Ω, inclusive, and 1,000 Ω, inclusive.

15. An inductively coupled pulsed radio frequency (RF) voltage multiplier circuit, comprising:

a plurality of switching circuits coupled to one another in parallel, each of the switching circuits including:

a switching circuit capacitor,

a switching circuit inductor, and

a switch;

a plurality of transformers, each of the transformers having a respective primary winding electrically coupled to a respective one of the switching circuits; and

a resonant circuit inductively coupled to the plurality of switching circuits through secondary windings of each of the plurality of transformers, the secondary windings of the plurality of transformers being electrically coupled to one another in series.

16. The pulsed RF voltage multiplier circuit of claim 1 wherein the resonant circuit includes an inductor and a capacitor electrically coupled in series to the secondary windings of the plurality of transformers.

17. The pulsed RF voltage multiplier circuit of claim 16 wherein the resonant circuit includes an inductance and a capacitor electrically coupled in series to the secondary windings of the plurality of transformers, the inductance including a leakage inductance due to uncoupled magnetic fields of the secondary windings of the transformers.

18. The pulsed RF voltage multiplier circuit of claim 15, further comprising a control circuit that selectively controls the switches of each of the plurality of switching circuits to concurrently switch from an electrically non-conducting state to an electrically conducting state.

19. The pulsed RF voltage multiplier circuit of claim 15, further comprising a diode opening switch electrically coupled to the resonant circuit.

20. The pulsed RF voltage multiplier circuit of claim 17, further comprising a load, wherein the diode opening switch is configured to deliver a RF voltage pulse to the load.

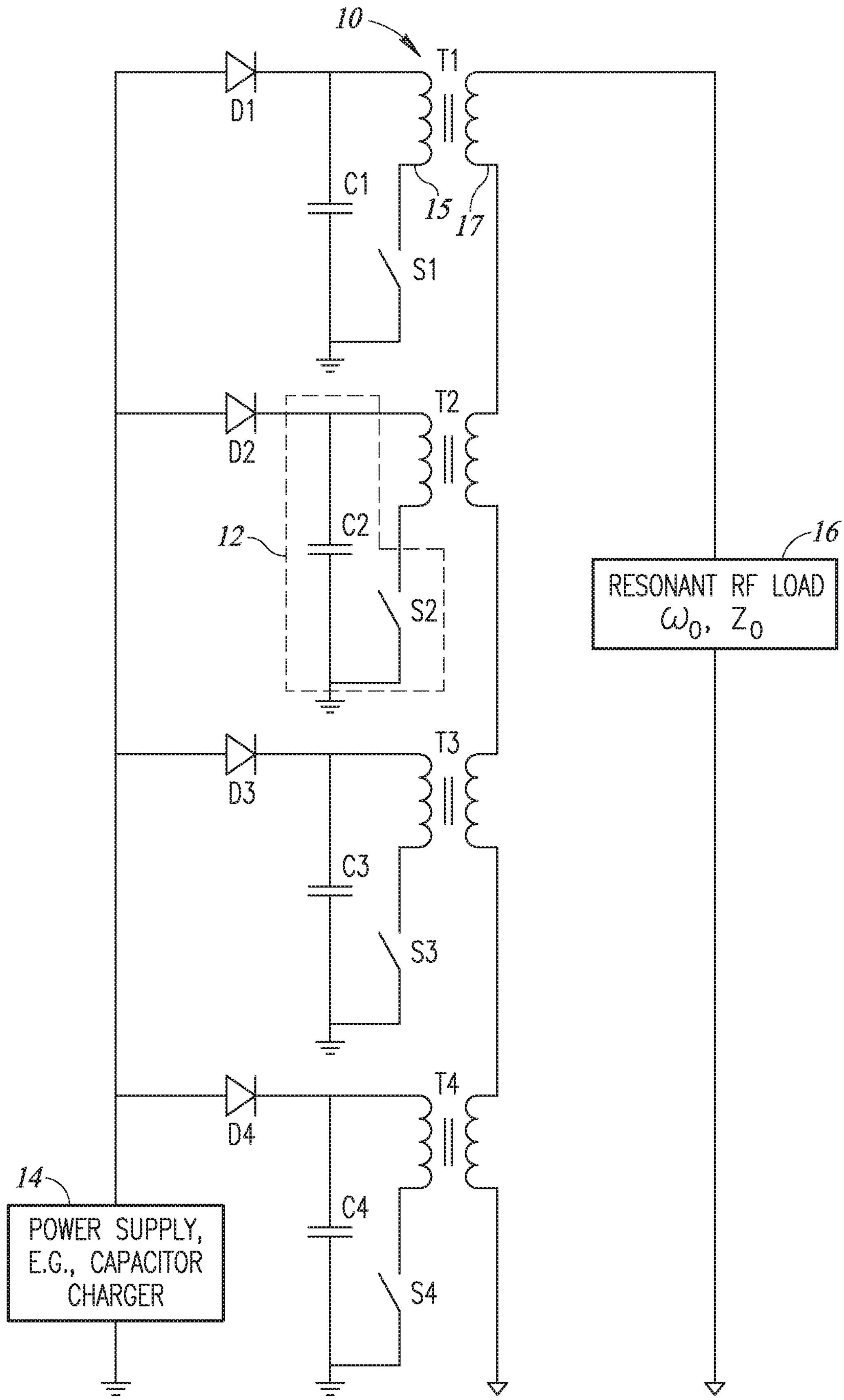
10
T1
D1
C1
15
17
S1
T2
D2
C2
12
S2
16
RESONANT RF LOAD
ω_0, Z_0
T3
D3
C3
S3
T4
D4
14
POWER SUPPLY,
E.G., CAPACITOR
CHARGER
C4
S4

FIG. 1

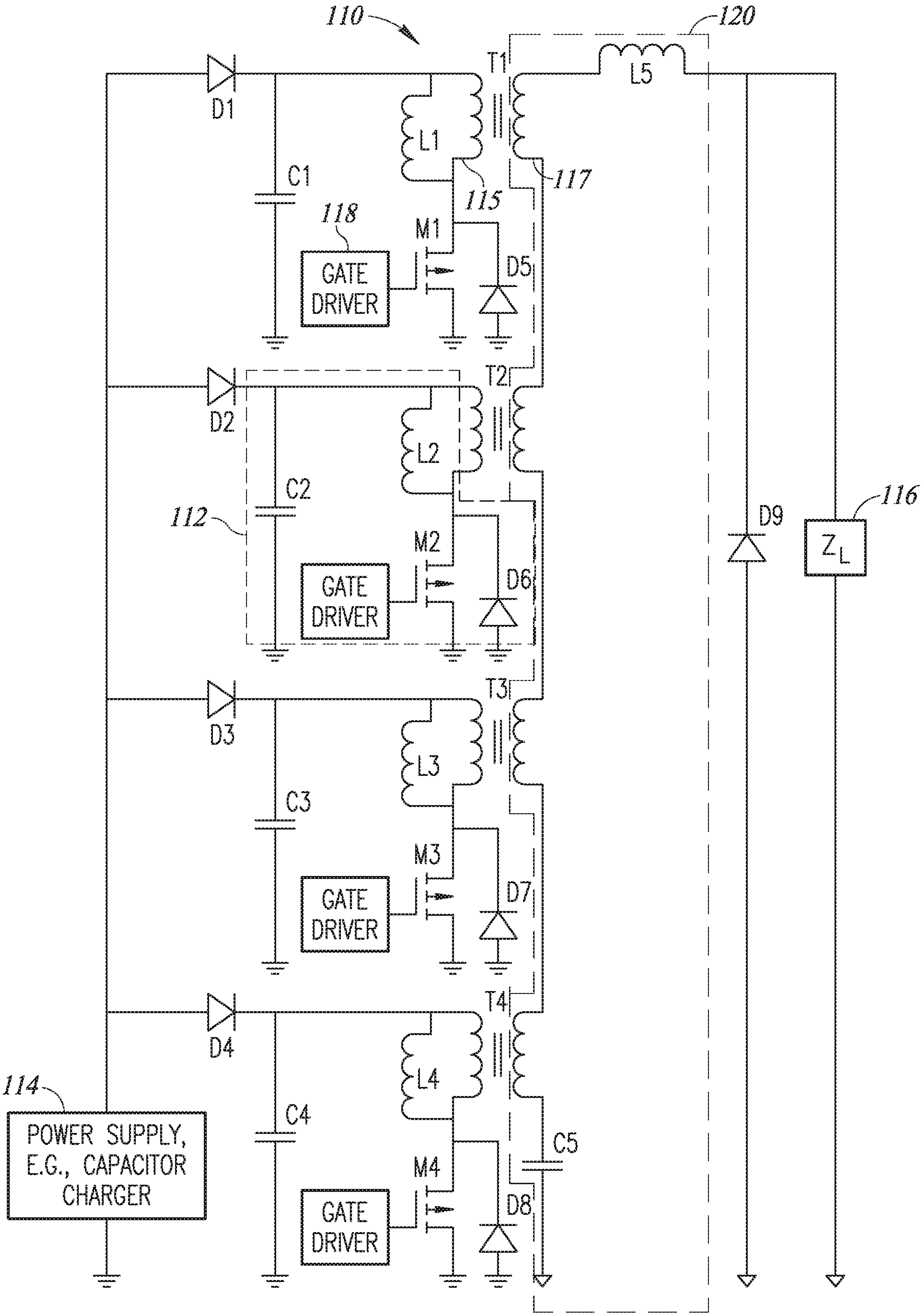
110
120
T1
L5
D1
L1
C1
117
115
118
M1
GATE DRIVER
D5
T2
D2
L2
C2
112
M2
GATE DRIVER
D6
D9
116
Z_L
T3
D3
L3
C3
M3
GATE DRIVER
D7
T4
D4
114
L4
POWER SUPPLY, E.G., CAPACITOR CHARGER
C4
C5
M4
GATE DRIVER
D8

FIG. 2

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2019/014273

A. CLASSIFICATION OF SUBJECT MATTER

H01J 37/32(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01J 37/32; A61B 18/12; H02M 1/08; H02M 1/42; H02M 3/335; H02M 7/44; H02M 7/68; H03B 19/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: mulltiply, capacitor, switch, inductor, resonant, transformer

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2014-0346875 A1 (UNIVERSITY OF FLORIDA RESEARCH FOUNDATION INC.) 27 November 2014 See paragraphs 84-90, and figure 3.	1-20
A	US 2016-0254754 A1 (MASSACHUSETTS INSTITUTE OF TECHNOLOGY) 01 September 2016 See paragraphs 51-53, and figure 7.	1-20
A	WO 2013-134573 A1 (MASSACHUSETTS INSTITUTE OF TECHNOLOGY) 12 September 2013 See paragraphs 144-146, and figure 26.	1-20
A	JP 2013-144127 A (COVIDIEN AG) 25 July 2013 See paragraphs 18-22, and figure 3.	1-20
A	US 2011-0267113 A1 (ROI CARMON et al.) 03 November 2011 See paragraphs 18-19, and figure 1.	1-20

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

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 May 2019 (09.05.2019)	**09 May 2019 (09.05.2019)**

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2019/014273

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