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Wang et al.

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(54) **BALANCED RF RESONANT ANTENNA SYSTEM**

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H01J 37/32 (2006.01)
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(52) **U.S. Cl.**
CPC .. ***H01J 37/32183*** (2013.01); ***H01J 37/32091*** (2013.01); ***H01Q 5/10*** (2015.01)

(58) **Field of Classification Search**
CPC H01J 37/32183; H01J 37/32091; H01J 37/3211; H01Q 5/10
See application file for complete search history.

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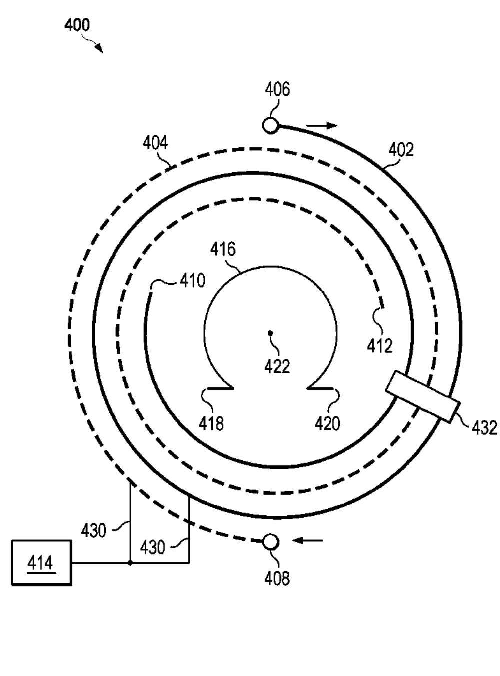
(57) **ABSTRACT**

According to an embodiment, a plasma processing system includes a plasma chamber, an RF source, a matching circuit, a balun, and a resonating antenna. The resonating antenna includes a first and a second spiral resonant antenna (SRA), each having an electrical length corresponding to a quarter of a wavelength of a frequency of a forward RF wave generated by the RF source. The first end of the first SRA is coupled to a first balanced terminal of the balun and the second end of the first SRA is open circuit. The first end of the second SRA is coupled to a second balanced terminal of the balun and the second end of the second SRA is open circuit. The first and the second SRA are arranged in a symmetrically nested configuration having a same center point.

20 Claims, 10 Drawing Sheets



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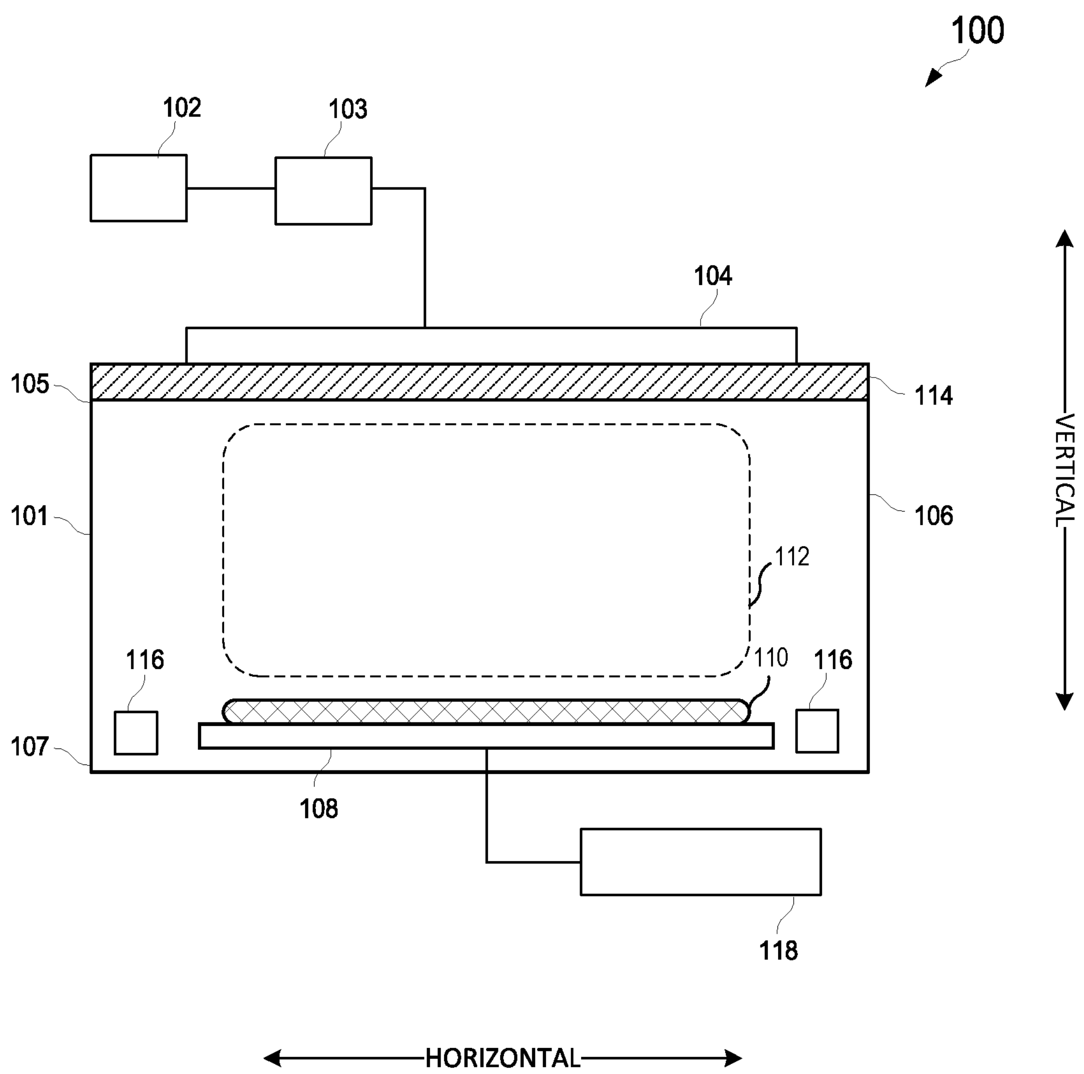

100
102
103
104
105
114
101
106
112
116
110
116
107
108
118
VERTICAL
HORIZONTAL

FIG. 1

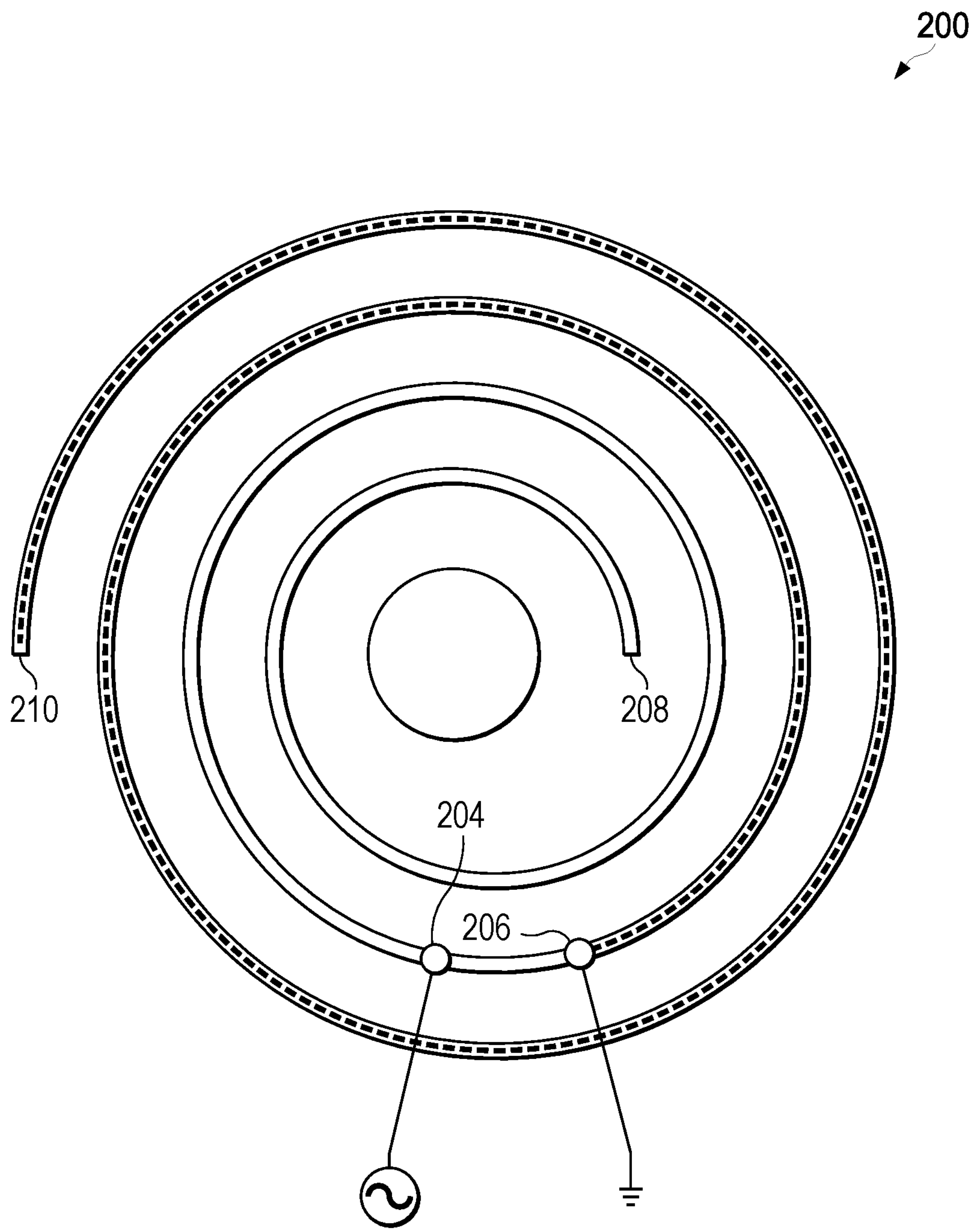


FIG. 2

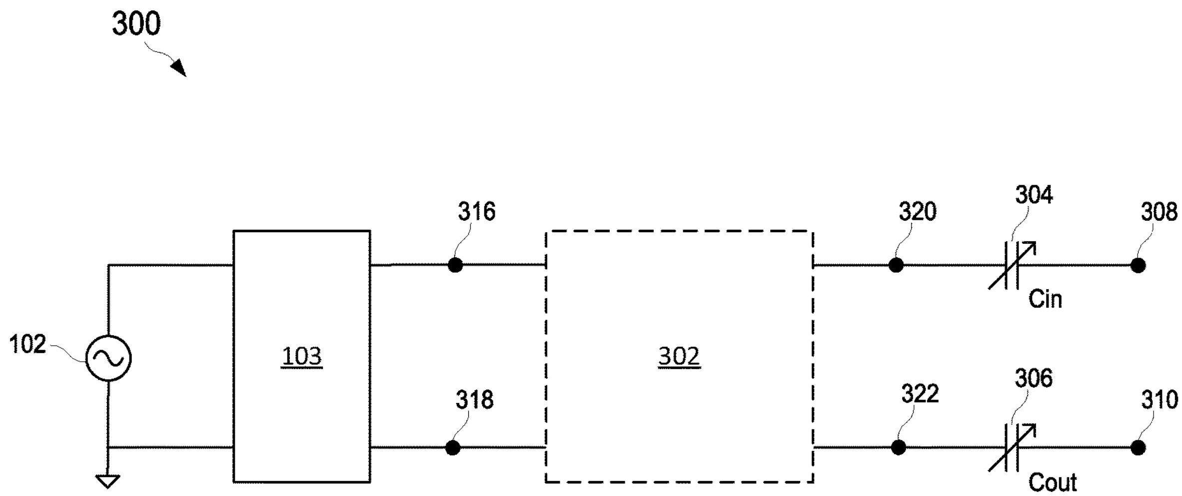


FIG. 3

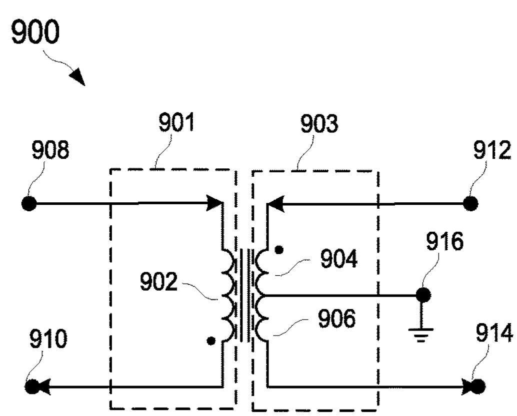


FIG. 9A

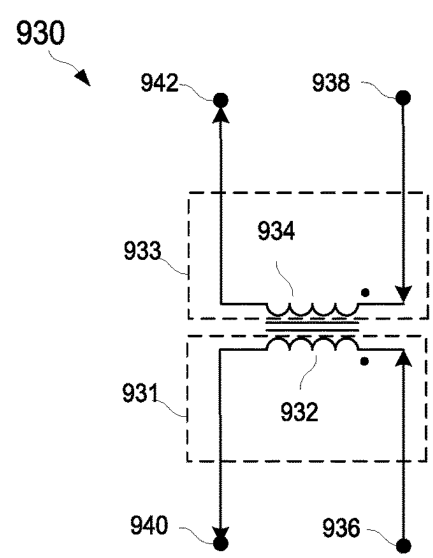


FIG. 9B

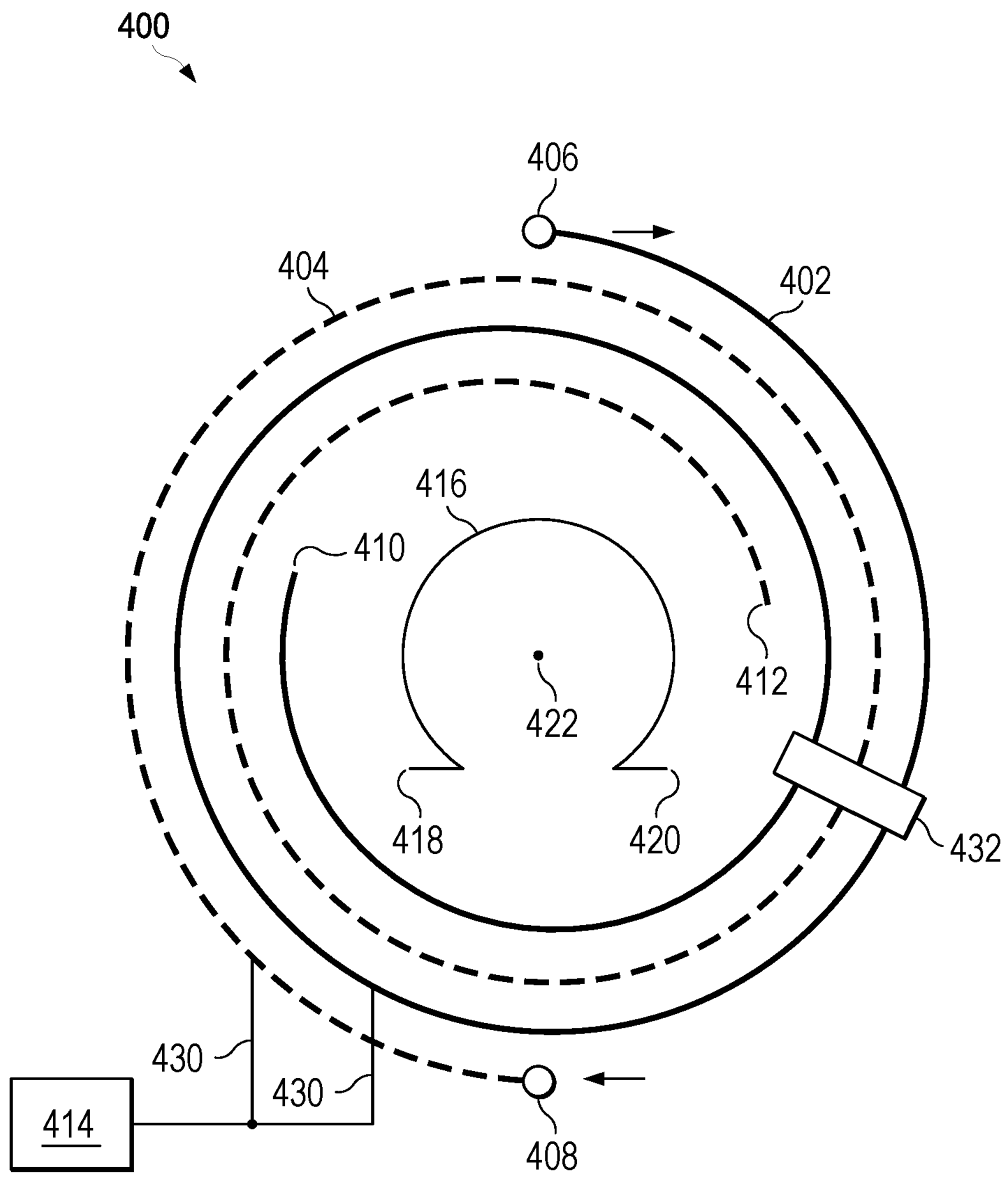
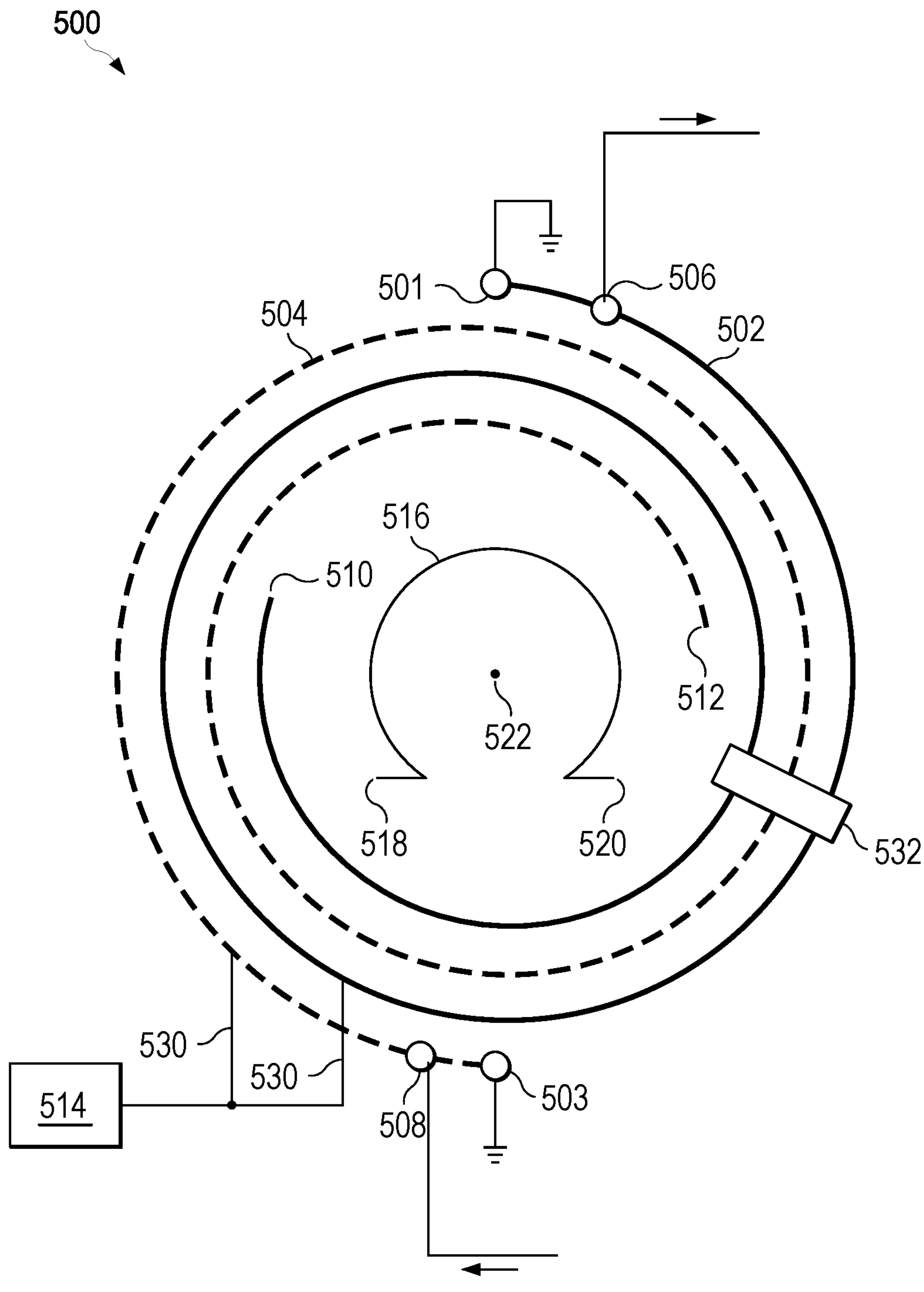


FIG. 4


500
501
506
504
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516
510
512
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520
532
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530
514
508
503

FIG. 5

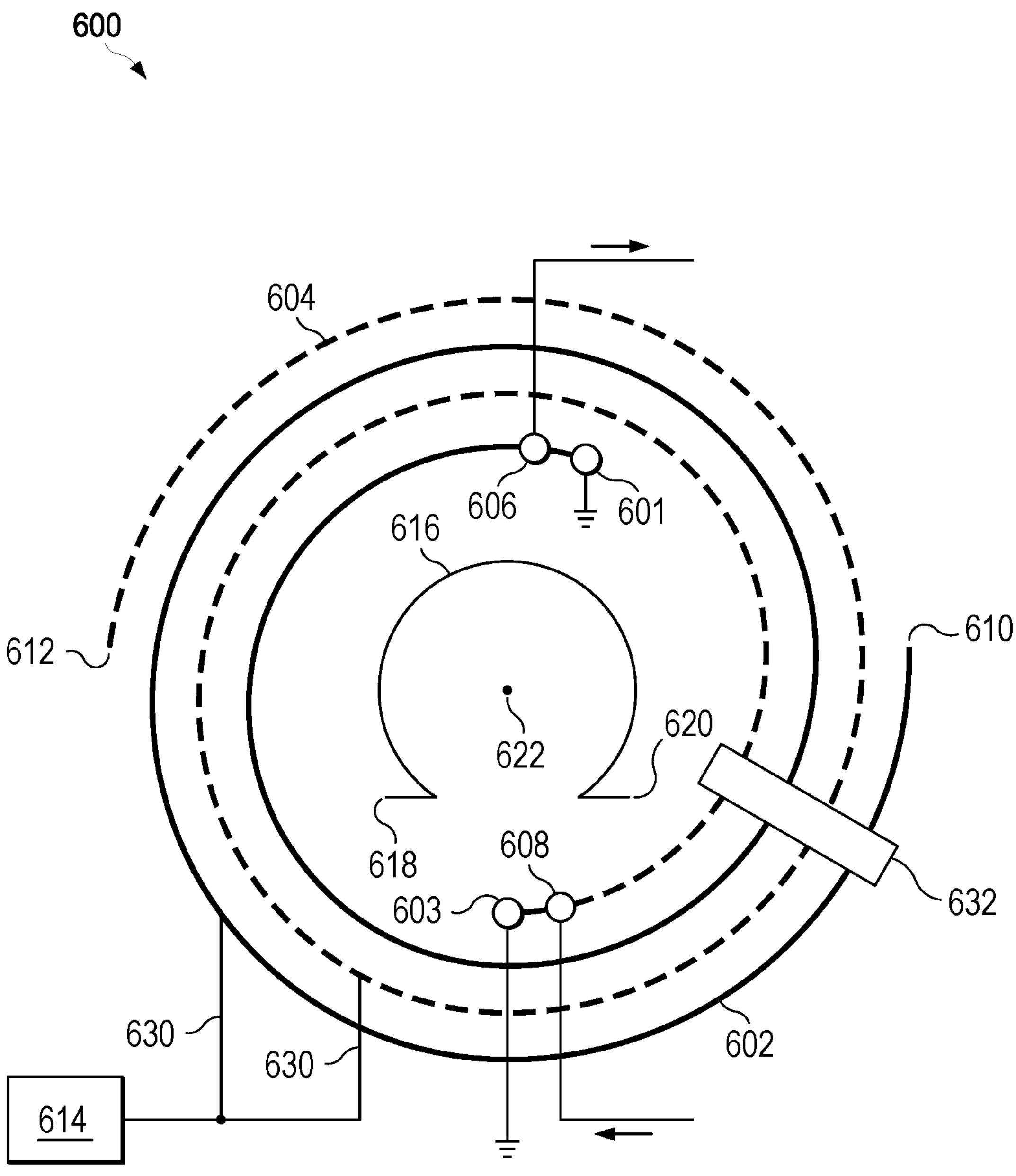
600
604
606
601
616
612
610
622
620
618
608
603
632
630
630
602
614

FIG. 6

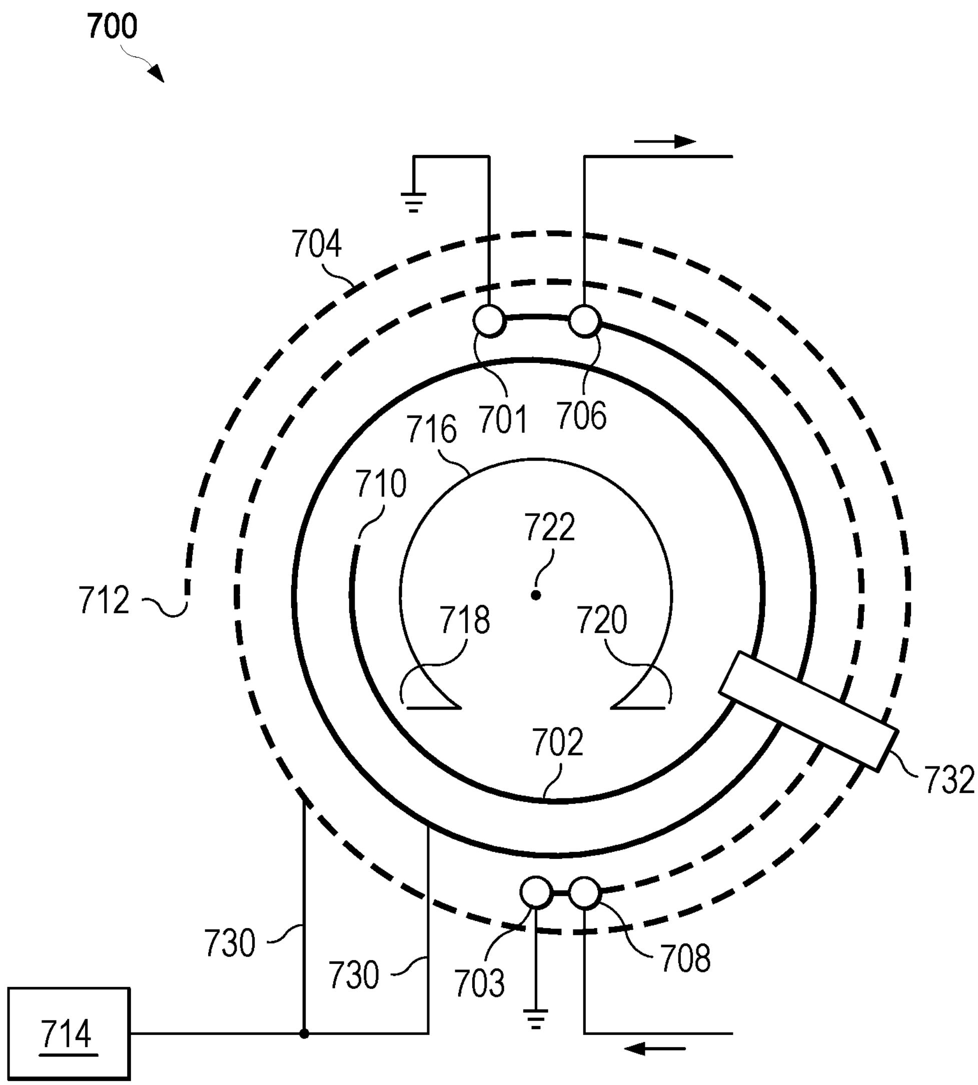
700
704
701
706
716
710
722
712
718
720
702
732
730
730
703
708
714

FIG. 7

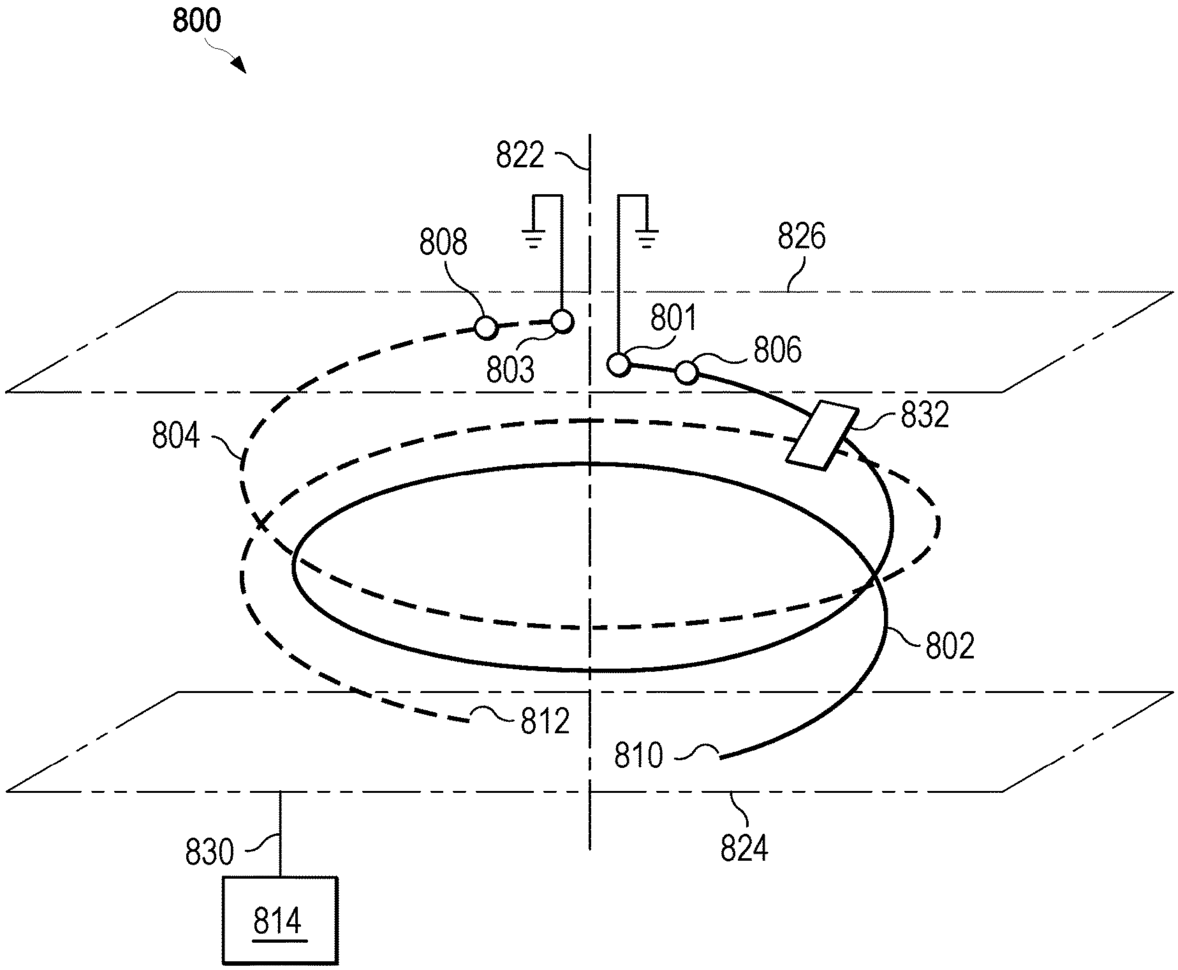

FIG. 8A

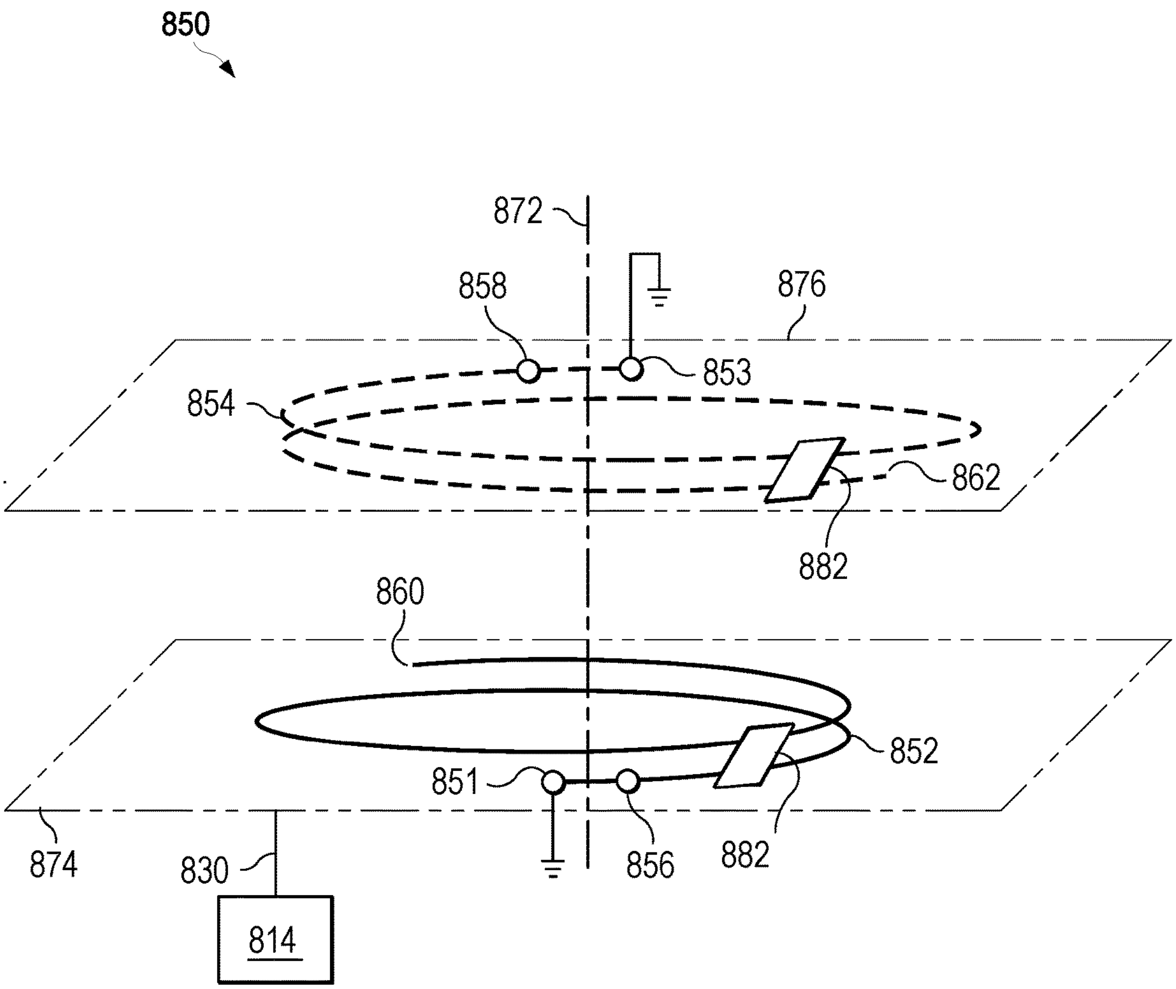

FIG. 8B

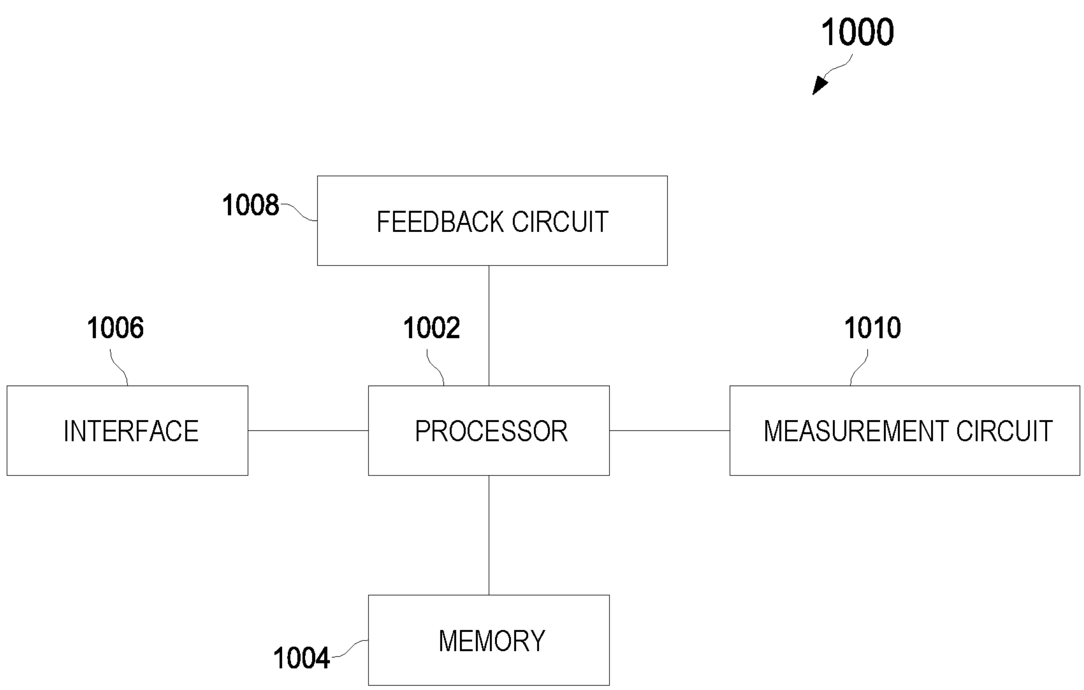
1000
1008
FEEDBACK CIRCUIT
1006
1002
1010
INTERFACE
PROCESSOR
MEASUREMENT CIRCUIT
MEMORY
1004

FIG. 10

BALANCED RF RESONANT ANTENNA SYSTEM

TECHNICAL FIELD

The present disclosure generally relates to plasma processing and, in particular embodiments, to a balanced RF resonant antenna system.

BACKGROUND

Plasma processing is extensively used in the manufacturing and fabricating of high-density microscopic circuits within the semiconductor industry. In a plasma processing system, an electromagnetic wave radiated into a plasma chamber generates an electromagnetic field. The generated electromagnetic field heats electrons in the chamber. The heated electrons ignite plasma that treats the substrate in a process such as etching, deposit, oxidation, sputtering, or the like.

A non-uniform electromagnetic field within the plasma processing chamber results in a non-uniform treatment of the substrate due to different portions of the substrate being treated with varying plasma densities. An apparatus and system that improves the uniformity of the electromagnetic field in a plasma processing system are, thus, desirable.

SUMMARY

Technical advantages are generally achieved by embodiments of this disclosure which describe a balanced RF resonant antenna system.

A first aspect relates to a plasma processing system. The plasma processing system includes a plasma chamber, an RF source, a matching circuit, a balun, and a resonating antenna. The RF source is configured to generate a forward RF wave. The matching circuit is coupled to the RF source and is configured to provide matching for the RF source. The balun includes unbalanced terminals coupled to the matching circuit. The resonating antenna is configured to generate plasma within the plasma chamber and includes a first spiral resonant antenna and a second spiral resonant antenna. The first spiral resonant antenna has an electrical length corresponding to a quarter of a wavelength of a frequency of the forward RF wave, a first end and a second end. The first end is coupled to a first balanced terminal of the balun and the second end is an open circuit. The second spiral resonant antenna has an electrical length corresponding to a quarter of the wavelength of the frequency of the forward RF wave, a first end and a second end. The first end is coupled to a second balanced terminal of the balun and the second end is an open circuit. The first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having the same center point.

A second aspect relates to a resonating antenna for generating plasma within a plasma chamber. The resonating antenna includes a first spiral resonant antenna having an electrical length corresponding to a quarter of a wavelength of a frequency of a forward RF wave fed by an RF source couplable to the resonating antenna. The first spiral resonant antenna has a first end and a second end. The first end couplable to a first balanced terminal of a balun and the second end is an open circuit. The second spiral resonant antenna has an electrical length corresponding to a quarter of the wavelength of the frequency of the forward RF wave. The second spiral resonant antenna has a first and second end, the first end couplable to a second balanced terminal of the balun and the second end is an open circuit. The first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having the same center point.

A third aspect relates to an apparatus for generating plasma in a plasma chamber of a plasma processing system. The apparatus includes an RF source configured to generate a forward RF wave; a matching circuit coupled to the RF source, the matching circuit configured to provide matching for the RF source; a balun having unbalanced terminals coupled to the matching circuit; a resonating antenna, the resonating antenna configured to generate plasma within the plasma chamber, the resonating antenna having: a first spiral resonant antenna having an electrical length corresponding to a quarter of a wavelength of a frequency of the forward RF wave, the first spiral resonant antenna having a first end and a second end, the first end coupled to a first balanced terminal of the balun and the second end that is open circuit, and a second spiral resonant antenna having an electrical length corresponding to the quarter of the wavelength of the frequency of the forward RF wave, the second spiral resonant antenna having a first end and a second end, the first end coupled to a second balanced terminal of the balun and the second end that is open circuit, wherein the first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having a same center point; a non-transitory memory storage comprising instructions; and a processor in communication with the non-transitory memory storage and coupled to the matching circuit, wherein the instructions, when executed by the processor, cause the processor to provide a matching impedance between the RF source and the resonating antenna.

Embodiments can be implemented in hardware, software, or in any combination thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present disclosure and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIG. **1** is a diagram of an embodiment plasma processing system;

FIG. **2** is a resonating antenna of a conventional coil-based system;

FIG. **3** is a schematic of an embodiment circuit;

FIG. **4** is an embodiment resonating antenna;

FIG. **5** is an embodiment resonating antenna;

FIG. **6** is an embodiment resonating antenna;

FIG. **7** is an embodiment resonating antenna;

FIG. **8**A is an embodiment resonating antenna;

FIG. **8**B is an embodiment resonating antenna;

FIG. **9**A is a schematic of an embodiment voltage balun transformer;

FIG. **9**B is a schematic of an embodiment current balun transformer; and

FIG. **10** illustrates a block diagram of an embodiment processing system.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

This disclosure provides many applicable inventive concepts that can be embodied in a wide variety of specific contexts. The particular embodiments are merely illustrative of specific configurations and do not limit the scope of the claimed embodiments. Features from different embodiments may be combined to form further embodiments unless noted otherwise.

Variations or modifications described in one of the embodiments may also apply to others. Further, various changes, substitutions, and alterations can be made herein without departing from the spirit and scope of this disclosure as defined by the appended claims.

While inventive aspects are described primarily in the context of resonating in a plasma processing system, the inventive aspects may similarly apply to fields outside the semiconductor industry. Plasma can treat and modify surface properties through functional group addition. For example, to treat surfaces for paint deposits, plasma can convert hydrophobic surfaces to hydrophilic surfaces. Further, the inventive aspects are not limited to plasma. For example, RF can be used to thaw frozen food or dry textiles, food, wood, or the like.

Embodiments of this disclosure advantageously provide a more uniform near-field electromagnetic flux (i.e., Poynting vector) than conventional systems, which results in, for example, improved plasma azimuthal uniformity. In embodiments, a balun transformer-based matching network is provided that advantageously delivers balanced currents to each section of the radiating antenna (generating the near-field electromagnetic flux), resulting in improved system stability.

Aspects of the disclosure provide a balanced circuit coupled to a resonating antenna. The resonating antenna includes a pair of quarter wavelength coils. The balanced circuit includes a balanced to unbalanced transformer (i.e., balun) coupled to a matching network. The combination of the balun and the matching network results in a balanced current in each coil section. The improvement in current balance in each coil, in comparison to the conventional systems, improves the plasma density uniformity in the plasma chamber.

In embodiments, a plasma processing system includes a plasma chamber, an RF source, a matching circuit, a balun, and a resonating antenna. The RF source is configured to generate a forward RF wave. The matching circuit is coupled to the RF source and is configured to provide matching for the RF source. The balun includes unbalanced terminals coupled to the matching circuit. The resonating antenna is configured to generate plasma within the plasma chamber and includes a first spiral resonant antenna and a second spiral resonant antenna.

In embodiments, the first and second spiral resonant antennas have an electrical length corresponding to a quarter of a wavelength of a frequency of the forward RF wave. Each of the spiral resonant antennas has a corresponding first end and a second end. The first end of the first spiral resonant antenna is coupled to a first balanced terminal of the balun and the second end of the first spiral resonant antenna is an open circuit. The first end of the second spiral resonant antenna is coupled to a second balanced terminal of the balun and the second end of the second spiral resonant antenna is an open circuit. The first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having the same center point. These and further details are discussed in greater detail below.

FIG. **1** illustrates a diagram of an embodiment plasma processing system **100**. Plasma processing system **100** includes an RF source **102**, a radiating antenna **104**, a plasma chamber **106**, and, optionally, a dielectric plate **114**, which may (or may not) be arranged as shown in FIG. **1**. Further, plasma processing system **100** may include additional components not depicted in FIG. **1**. The plasma processing system **100**, in embodiments, may be housed within an enclosure, which may be a Faraday cage or a solid enclosure.

RF source **102** provides forward RF waves to the radiating antenna **104**. The forward RF waves travel through the radiating antenna **104** and are transmitted (i.e., radiated) towards plasma chamber **106**. In embodiments, the operating frequency of RF source **102** is set, but not limited to, 1 megahertz (MHz) to 400 MHz. In an embodiment, RF source **102** operates at 13.56 MHz. In an embodiment, RF source **102** operates at 27 MHz. In embodiments, the RF source **102** is a pulse-modulated. In such embodiments, the modulation frequency range is between, but not limited to, 10 hertz (Hz) and 20 kilohertz (20 kHz), inclusive. In embodiments, the modulation duty ratio range is between 10 and 90%, inclusive.

The plasma chamber **106** may include sidewalls **101**, a base **107**, and a top cover **105**, which may be made of a conductive material, for example, stainless steel or aluminum coated with a film, such as yttria (e.g., Y_xO_y or $Y_xO_yF_z$, etc.), or a film consistent with the process (e.g., carbon, silicon, etc.), or as known to a person of ordinary skill in the art. In embodiments, plasma chamber **106** is cylindrical with a base **107** and a top cover **105** that are circular.

The plasma chamber **106** includes a substrate holder **108** (i.e., chuck). As shown, substrate **110** is placed on substrate holder **108**, positioned at the base **107** of the plasma chamber **106**, to be processed. Optionally, plasma chamber **106** may include a bias power supply **118** coupled to the substrate holder **108**. Optionally, plasma chamber **106** may include one or more pump outlets **116** to remove by-products from plasma chamber **106** through selective control of gas flow rates within. In embodiments, pump outlets **116** are placed near (e.g., below/around the perimeter of) substrate holder **108** and substrate **110**. In embodiments, plasma chamber **106** may include additional substrate holders (not shown). In embodiments, the placement of the substrate holder **108** may differ from that shown in FIG. **1**. Thus, the quantity and position of the substrate holder **108** are non-limiting.

In embodiments, radiating antenna **104** is separated from the top cover **105** of the plasma chamber **106** by the dielectric plate **114** (i.e., a dielectric window), typically made of a dielectric material such as quartz. Dielectric plate **114** separates the low-pressure environment within plasma chamber **106** from the external atmosphere. It should be appreciated that radiating antenna **104** can be placed directly adjacent to the top cover **105** of the plasma chamber **106**, or radiating antenna **104** can be separated from plasma chamber **106** by air. In embodiments, the dielectric plate **114** is selected to minimize reflections of the RF wave from the plasma chamber **106**. In other embodiments, the radiating antenna **104** is embedded within the dielectric plate **114**.

In embodiments, radiating antenna **104** radiates an electromagnetic field towards the plasma chamber **106**. The radiated electromagnetic field generates a high-density plasma **112**. In embodiments, the excitation frequency of the radiating antenna **104** is in the radio frequency range (1-400 MHz), which is not limiting, and other frequency ranges can similarly be contemplated. For example, inventive aspects disclosed herein equally apply to applications in the microwave frequency range.

In embodiments, the radiating antenna **104** includes resonating coils. The resonating coils can be circular and coupled to RF source **102** through an intermediary circuit.

The resonating antennas are resonant with electromagnetic waves fed from the RF source **102**.

In embodiments, the resonating coils of the radiating antenna **104** are arranged about a central axis of symmetry. In an embodiment, the central axis of symmetry is perpendicular to the dielectric plate **114**. In an embodiment where the dielectric plate **114** is in the shape of a disk, the central axis of symmetry passes through the disk's center.

In embodiments, RF source **102** couples energy to an interface of the radiating antenna **104** to generate the standing electromagnetic waves from the radiating antenna **104**. The RF source **102** is coupled to the interface via a transmission line in embodiments. It is desirable that the interface maintain the same or higher symmetry as the elements of the radiating antenna **104** under rotation about the axis of symmetry.

In an embodiment, the radiating antenna **104** couples RF power from RF source **102** to the plasma chamber **106** to treat substrate **110**. In particular, radiating antenna **104** radiates an electromagnetic wave in response to being fed the forward RF waves from the RF source **102**. The radiated electromagnetic wave penetrates from the atmospheric side (i.e., radiating antenna **104** side) of the dielectric plate **114** into plasma chamber **106**. The radiated electromagnetic wave generates an electromagnetic field within the plasma chamber **106**. The generated electromagnetic field ignites and sustains plasma **112** by transferring energy to free electrons within plasma chamber **106**. The plasma **112** can be used to, for example, selectively etch or deposit material on substrate **110**.

In FIG. **1**, radiating antenna **104** is external to the plasma chamber **106**. In embodiments, however, radiating antenna **104** can be placed internally in plasma chamber **106**. In embodiments, radiating antenna **104** is a resonating antenna, operating, for example, at its resonant frequency.

In embodiments, the operating frequency of radiating antenna **104** is between 5 and 100 megahertz (MHz). In embodiments, the power delivered by radiating antenna **104** ranges from 10 to 5000 Watts (W)—determined by various factors such as distance from the radiating antenna **104**, impedance values, or the like.

FIG. **2** illustrates a resonating antenna **200** of a conventional coil-based system. Resonating antenna **200** is arranged as a half-wave resonant antenna. Resonating antenna **200** is a spiral conductive structure with an electrical length that is substantially equal to a half resonant frequency wavelength (i.e., half-wave). A uniform transmission line, similar to the resonating antenna **200**, of length L, terminated by open circuits at the two ends is a half-wavelength resonator. A half-wavelength resonator exhibits resonance at discrete frequencies corresponding to L being equal to a multiple of one-half of a wavelength (λ) or $L=n\times\lambda/2$, where n is a whole number.

Resonating antenna **200** includes multiple taps along its length, which allows a circuit to make physical and electrical contact with the resonating antenna **200**. RF source **102** is couplable to the first node **204** via the matching circuit **103** and RF ground is couplable to the second node **206**. The ends of the resonating antenna **200** are labeled as the third node **208** (i.e., at the inner portion of the spiral conductive structure) and the fourth node **210** (i.e., at the outer portion of the spiral conductive structure). The third node **208** and the fourth node **210** are left floating (i.e., open circuit). The first node **204** and second node **206** are arranged such that they are equidistant from the ends (i.e., third node **208** and fourth node **210**) of the spiral conductive structure along the length of the resonating antenna **200**.

The first node **204** and second node **206** effectively split the resonating antenna **200** into two coils: (i) an inner coil portion from the first node **204** to the third node **208**, at one end of the resonating antenna **200** and (ii) an outer coil portion from the second node **206** to the fourth node **210**, at a second end of the resonating antenna **200**.

Due to the asymmetry in the layout of resonating antenna **200**, the plasma generated could be non-uniform. Further, as the current flowing through the inner coil portion and outer coil portion could be unbalanced under certain operating conditions, the non-uniformity of the plasma generated by resonating antenna **200** is increased.

FIG. **3** illustrates a schematic of an embodiment circuit **300**. Circuit **300** includes the RF source **102**, the matching circuit **103**, a balun (balanced-to-unbalanced conversion circuit) **302**, and, optionally, a capacitor **304** and a capacitor **306** which may (or may not) be arranged as shown. Circuit **300** may include additional components not shown, such as inductors. Circuit **300** is couplable, at the first terminal **308** and the second terminal **312**, to the radiating antenna **104**. In embodiments, the optional capacitors **304**, **306** are replaced with inductors.

RF source **102** includes an RF power supply, which may include a generator circuit. In embodiments, RF source **102**, matching circuit **103**, balun **302**, and capacitors **304**, **306** are coupled via a power transmission line, such as a coaxial cable, or the like. RF source **102** is configured to generate a forward RF wave to the radiating antenna **104** couplable to circuit **300** at terminals **308**, **312**.

When a wave travels through a medium, an impedance discontinuity caused, for example, by a transition from one medium to another results in a portion of the wave being reflected into the original medium from which the wave is traveling. The parameter used to define this ratio is the reflection coefficient. It is advantageous for RF power from the RF source **102** to be fed to the plasma chamber **106** with minimal reflection and for the reflection coefficient at the impedance discontinuities to be as low as possible.

An impedance associated with the plasma **112**, generated in the plasma chamber **106**, corresponds to the load of the radiating antenna **104** during its operation. The impedance of the plasma **112** can vary based on, for example, changes in pressure, temperature, increased or decreased gas flow rates, or operating conditions.

Typically, a matching circuit **103** (auto or manual) coupled to the radiating antenna **104** is used to minimize losses (i.e., reflected power) in response to changes in the load condition. Matching circuit **103** may include one or more transformers, resistor networks, capacitors, inductors (i.e., reactive components), or fixed-length transmission lines, which may be arranged as known in the art. In embodiments, the components are adjustable (e.g., variable capacitors, etc.) that allow the matching circuit **103** to be updated (i.e., provide a variable impedance) based on the operating condition (e.g., operating frequency) of the plasma processing system **100**. In some embodiments, an automatic (i.e., dynamic) tuning algorithm controls the operation and configuration of the matching circuit **103**. In embodiments, the matching circuit **103** is manually configured based on the operating condition of the plasma processing system **100**.

Balun **302** allows for a differential, balanced RF functional block, for example, the resonating antennas in the present disclosure, to couple to the single-ended, ground-reference (e.g., RF source **102**/matching circuit **103** and RF ground). In embodiments, balun **302** is configured to match the balanced impedance at the radiating antenna **104** to the unbalanced impedance of the RF source **102** and its associated circuits (i.e., including matching circuit **103**), which are configured to deliver the RF power to the radiating antenna **104**. The unbalanced terminals of the balun **302** are coupled to the matching circuit **103** via terminals **316** and **318** and the balanced terminals of the balun **302** are coupled to the capacitors **304** and **306** via terminals **320** and **322**.

In embodiments, circuit **300** includes blocking capacitors **304** and **306** that block a DC current flowing between the balun **302** and the radiating antenna couplable at terminals **308**, **312**. Capacitors **304**, **306**, and balun **302**, combined with the matching circuit **103**, provide an improved circuit **300** for matching RF source **102** with a radiating antenna **104** couplable at terminals **308** and **312**.

FIG. **4** illustrates an embodiment resonating antenna **400**, which may be arranged in the plasma processing system **100** for the radiating antenna **104**. Resonating antenna **400** includes a pair of spiral resonant antennas, each configured as a quarter-wavelength resonator. The first one of the pair of spiral resonant antennas is the first coil **402** (also referred to as the inner coil). A second one of the pair of spiral resonant antennas is the second coil **404** (also referred to as the outer coil). The first coil **402** and the second coil **404** are shown to be substantially on the same plane and nested within each other. The nested arrangement effectively places each turn of the first coil **402** adjacent to a respective turn of the second coil **404**. Each coil **402**, **404** may have one or more turns to form the respective spiral resonant antenna. Thus, the number of turns for each coil **402**, **404** is non-limiting. In embodiments, the current flow path in the resonating antenna **400** is from circuit **300** at the first end **408** to the second coil **404** and from the first coil **402** to circuit **300** at the first end **406**.

In embodiments, the resonating antenna **400** is arranged on a plane parallel to the top cover **105** of the plasma chamber **106**. In embodiments, the resonating antenna **400** is coupled to a mechanical structure **414** (e.g., an actuator) that allows the resonating antenna **400** to be vertically adjusted with respect to the top cover **105** while remaining parallel to the top cover **105**. In embodiments, the matching circuit **103**, the capacitors **304**, **306**, and balun **302** are configurable to provide an improved match based on a change at the load in response to the adjustment of the resonating antenna **400**.

The first coil **402** and the second coil **404** are spiral conductive structures. In embodiments, the electrical lengths of the first coil **402** and the second coil **404** are substantially equal to a quarter resonant frequency wavelength (i.e., quarter-wave). In embodiments, the first coil **402** and the second coil **404** are arranged symmetrically with respect to a center point **422** defining the spiral structure of each coil. In embodiments, the first coil **402** and the second coil **404** are arranged as planar spiral conductive coils. In embodiments, the first coil **402** and the second coil **404** are intertwined on the same plane configured to radiate the electromagnetic wave.

The first terminal **308** of circuit **300** is couplable to the first end **406** of the first coil **402**, where the first end **406** is at an outer portion of the first coil **402**. The second terminal **310** of circuit **300** is couplable to the first end **408** of the second coil **404**, where the first end **408** is at an outer portion of the second coil **404**. In embodiments, the second end **410** of the first coil **402** and the second end **412** of the second coil **404** are floating (i.e., open circuit), where the second end **410** is at an inner portion (i.e., near the center point **422**) of the first coil **402**, and where the second end **412** is at an inner portion of the second coil **404**. In embodiments, the second ends **410**, **412** are couplable to a reference ground.

In embodiments, the first coil **402** and the second coil **404** are arranged in a nested configuration. In embodiments, the first coil **402** and the second coil **404** are arranged in an interwoven (i.e., braided) configuration but electrically isolated. In embodiments, the second coil **404** is arranged such that a radial distance from any point, along the length of the second coil **404**, is equally separated (i.e., equidistance) from the first coil **402**.

In embodiments, the first coil **402** and the second coil **404** are substantially on the same plane. In embodiments, the first coil **402** and the second coil **404** are on different planes that are substantially perpendicular to each other. In embodiments, the first coil **402** and the second coil **404** have a common center point **422** at the center of the spiral conductive structure. In embodiments, the first coil **402** and the second coil **404** are conical coils arranged such that the conical coils have a first common plane at the base and a second common plane at the top. In embodiments, the first coil **402** and the second coil **404** are cylindrical coils arranged such that the cylindrical coils have a first common plane at the base and a second common plane at the top.

In embodiments, the first ends **406** and **408** are substantially on a first plane and 180 degrees offset. In embodiments, the second ends **410** and **412** are substantially on a second plane and 180 degrees offset. In embodiments, the first end **406** is offset from the second end **410** in the first coil **402** such that the electrical length of the first coil **402** corresponds to a quarter resonant frequency wavelength. In embodiments, the first end **408** is offset from the second end **412** in the second coil **404** such that the electrical length of the second coil **404** corresponds to a quarter resonant frequency wavelength. In embodiments, the first and the second planes are the same planes. In embodiments, the first and second planes are offset from each with a distance that results in a quarter-wave electrical length for the first coil **402** and the second coil **404**.

In embodiments, the first coil **402** and the second coil **404** have a design corresponding to an arc or a spiral, for example, an Archimedean, an equiangular, an Euler, a Cornu, a Clothoid, a Cotes, a Fermat, a parabolic, a lituus, a Poinsot, a reciprocal, a hyperbolic, a logarithmic, or a sinusoidal spiral forming a spiral antenna. However, the design of the resonating antenna **400** is non-limiting. As another example, the resonating antenna **400** can be a single-coil arc plate, a double-coil arc plate, or a unibody arc plate.

In embodiments, each of the first coil **402** and the second coil **404** are a solid conductive plate having cutouts to form the respective coils. In embodiments, a non-conductive structure (e.g., a non-conductive plate with cutouts to hold the first coil **402** and the second coil **404**) provides structural support to arrange the first coil **402** within the inner radius of the second coil **404**.

In embodiments, vertical non-conductive structures **430** (e.g., non-conductive offsets perpendicular to the first coil **402** and the second coil **404**) are structurally coupled to the first coil **402** and the second coil **404**. In embodiments, horizontal non-conductive structures **432** provide structural support to separate the first coil **402** from the second coil **404** at an equidistance along the spiral structures. In embodiments, the second ends **410**, **412** of the first coil **402** and the second coil **404**, respectively, are floating. The vertical non-conductive structures **430** and the horizontal non-conductive structures **432** may be arranged on any position along the length of the first coil **402**, the second coil **404**, or both. In embodiments, the vertical non-conductive structures **430** are configurable to vertically adjust the plane on which the resonating antenna **400** is arranged with respect (substantially parallel) to the top cover **105** of the plasma chamber **106**. In embodiments, each of the first coil **402** and the second coil **404** includes a wire arranged in a spiral configuration. The first end of the wire of each of the first coil **402** and the second coil **404** is couplable to a respective terminal (i.e., terminals **308** and **310**) of circuit **300**.

Resonating antenna **400** is arranged as a dual spiral quarter-wavelength resonator, where first ends **406**, **408** of each coil **402**, **404** is couplable to the balun **302**, and a second end **410**, **412** of each coil **402**, **404** is left as an open circuit. A quarter-wavelength resonator exhibits resonance at discrete frequencies corresponding to L (the physical length of each coil **402**, **404**) equal to a multiple of one-quarter of a wavelength (λ) or

$$L = n \times \frac{\lambda}{4},$$

where n is a whole number. Here, the frequency corresponds to the frequency of the RF wave directed from the RF source **102** couplable to the resonating antenna **400**. In embodiments, the physical length of the first coil **402** is substantially equal to the physical length of the second coil **404**. In embodiments, the physical length of the first coil **402** is different from that of the second coil **404**.

Resonating antenna **400**, optionally, includes a third coil **416** nested within a central position in an inner portion of each of the first coil **402** and the second coil **404**. The third coil **416** has a first end **418** and a second end **420** that is grounded. In embodiments, the third coil **416** is substantially on the same plane as the first coil **402**, the second coil **404**, or the first coil **402** and the second coil **404**. In embodiments, the first coil **402**, second coil **404**, and the third coil **416** are symmetrically arranged, such that each coil shares the same center point **422**.

FIG. **5** illustrates an embodiment resonating antenna **500**, which may be arranged in the plasma processing system **100** for the radiating antenna **104**. Resonating antenna **500** includes a pair of spiral resonant antennas, each configured as a quarter-wavelength resonator. The first one of the pair of spiral resonant antennas is the first coil **502** (also referred to as the inner coil). A second one of the pair of spiral resonant antennas is the second coil **504** (also referred to as the outer coil). The first coil **502** and the second coil **504** are shown to be substantially on the same plane and nested within each other. The nested arrangement effectively places each turn of the first coil **502** adjacent to a respective turn of the second coil **504**. Each coil **502**, **504** may have one or more turns to form the respective spiral resonant antenna. Thus, the number of turns for each coil **502**, **504** is non-limiting. In embodiments, the current flow path in the resonating antenna **500** is from circuit **300** at terminal **508** to the second coil **504** and from the first coil **502** to circuit **300** at terminal **506**.

In embodiments, the resonating antenna **500** is arranged on a plane parallel to the top cover **105** of the plasma chamber **106**. In embodiments, the resonating antenna **500** is coupled to a mechanical structure **514** (e.g., an actuator) that allows the resonating antenna **500** to be vertically adjusted with respect to the top cover **105** while remaining parallel to the top cover **105**. In embodiments, the matching circuit **103**, the capacitors **304**, **306**, and balun **302** are configurable to provide an improved match based on a change at the load in response to the adjustment of the resonating antenna **500**.

The first coil **502** and the second coil **504** are spiral conductive structures. In embodiments, the electrical lengths of the first coil **502** and the second coil **504** are substantially equal to a quarter resonant frequency wavelength (i.e., quarter-wave). In embodiments, the first coil **502** and the second coil **504** are arranged symmetrically with respect to a center point **522** defining the spiral structure of each coil. In embodiments, the first coil **502** and the second coil **504** are arranged as planar spiral conductive coils. In embodiments, the first coil **502** and the second coil **504** are intertwined on the same plane configured to radiate the electromagnetic wave.

A first end **501** of the first coil **502** and a first end **503** of the second coil **504** are couplable to a reference ground. The first terminal **308** of circuit **300** is couplable to terminal **506** of the first coil **502**, where terminal **506** is at an outer portion of the first coil **502** and at a distance between 1 cm to 10 cm from the first end **501**. The second terminal **310** of circuit **300** is couplable to terminal **508** of the second coil **504**, where terminal **508** is at an outer portion of the second coil **504** and at a distance between 1 cm to 10 cm from the first end **503**. In embodiments, the second end **510** of the first coil **502** and the second end **512** of the second coil **504** are floating (i.e., open circuit), where the second end **510** is at an inner portion (i.e., near the center point **522**) of the first coil **502**, and where the second end **512** is at an inner portion of the second coil **504**. In embodiments, the second ends **510**, **512** are couplable to a reference ground

In embodiments, the first coil **502** and the second coil **504** are arranged in a nested configuration. In embodiments, the first coil **502** and the second coil **504** are arranged in an interwoven (i.e., braided) configuration but electrically isolated. In embodiments, the second coil **504** is arranged such that a radial distance from any point, along the length of the second coil **504**, is equally separated (i.e., equidistance) from the first coil **502**.

In embodiments, the first coil **502** and the second coil **504** are substantially on the same plane. In embodiments, the first coil **502** and the second coil **504** are on different planes that are substantially perpendicular to each other. In embodiments, the first coil **502** and the second coil **504** have a common center point **522** at the center of the spiral conductive structure. In embodiments, the first coil **502** and the second coil **504** are conical coils arranged such that the conical coils have a first common plane at the base and a second common plane at the top. In embodiments, the first coil **502** and the second coil **504** are cylindrical coils arranged such that the cylindrical coils have a first common plane at the base and a second common plane at the top.

In embodiments, the first ends **501** and **503** are substantially on a first plane and 180 degrees offset. In embodiments, the second ends **510** and **512** are substantially on a second plane and 180 degrees offset. In embodiments, the first end **501** is offset from the second end **510** in the first coil **502** such that the electrical length of the first coil **502** corresponds to a quarter resonant frequency wavelength. In embodiments, the first end **503** is offset from the second end **512** in the second coil **504** such that the electrical length of the second coil **504** corresponds to a quarter resonant frequency wavelength. In embodiments, the differential current mode is achieved when the first coil **502** and the second coil **504** are physically connected to RF power input at **506** and **508**, respectively through the current balun (e.g., FIG. **9**B). In embodiments, the first and the second planes are the same planes.

In embodiments, the first coil **502** and the second coil **504** have a design corresponding to an arc or a spiral, for example, an Archimedean, an equiangular, an Euler, a Cornu, a Clothoid, a Cotes, a Fermat, a parabolic, a lituus, a Poinsot, a reciprocal, a hyperbolic, a logarithmic, or a sinusoidal spiral forming a spiral antenna. However, the design of the resonating antenna **500** is non-limiting. As another example, the resonating antennas can be a single-coil arc plate, a double-coil arc plate, or a unibody arc plate.

In embodiments, each of the first coil **502** and the second coil **504** are a solid conductive plate having cutouts to form the respective coils. In embodiments, a non-conductive structure (e.g., a non-conductive plate with cutouts to hold the first coil **502** and the second coil **504**) provides structural support to arrange the first coil **502** within the inner radius of the second coil **504**.

In embodiments, vertical non-conductive structures **530** (e.g., non-conductive offsets perpendicular to the first coil **502** and the second coil **504**) are structurally coupled to the first coil **502** and the second coil **504**. In embodiments, horizontal non-conductive structures **532** provide structural support to separate the first coil **502** from the second coil **504** at an equidistance along the spiral structures. In embodiments, the second ends **510**, **512** of the first coil **502** and the second coil **504**, respectively, are floating. The vertical non-conductive structures **530** and the horizontal non-conductive structures **532** may be arranged on any position along the length of the first coil **502**, the second coil **504**, or both. In embodiments, the vertical non-conductive structures **530** are configurable to vertically adjust the plane on which the resonating antenna **500** is arranged with respect (substantially parallel) to the top cover **105** of the plasma chamber **106**. In embodiments, each of the first coil **502** and the second coil **504** includes a wire arranged in a spiral configuration. The terminals **506**, **508** of each of the first coil **502** and the second coil **504**, respectively, are couplable to a respective terminal (i.e., terminals **308** and **310**) of circuit **300**.

Resonating antenna **500** is arranged as a dual spiral quarter-wavelength resonator, where terminals **506**, **508** of each coil **502**, **504** is couplable to the balun **302**, and a second end **510**, **512** of each coil **502**, **504** is left as an open circuit. A quarter-wavelength resonator exhibits resonance at discrete frequencies corresponding to L (the physical length of each coil **502**, **504**) equal to a multiple of one-quarter of a wavelength (λ) or

$$L = n \times \frac{\lambda}{4},$$

where n is a whole number. Here, the frequency corresponds to the frequency of the RF wave directed from the RF source **102** couplable to the resonating antenna **500**. In embodiments, the physical length of the first coil **502** is substantially equal to the physical length of the second coil **504**. In embodiments, the physical length of the first coil **502** is different from the physical length of the second coil **504**.

Resonating antenna **500**, optionally, includes a third coil **516** nested within a central position in an inner portion of each of the first coil **502** and the second coil **504**. The third coil **516** has a first end **518** and a second end **520** that is grounded. In embodiments, the third coil **516** is substantially on the same plane as the first coil **502**, the second coil **504**, or the first coil **502** and the second coil **504**. In embodiments, the first coil **502**, second coil **504**, and the third coil **516** are symmetrically arranged, such that each coil shares the same center point **522**.

FIG. **6** illustrates an embodiment resonating antenna **600**, which may be arranged in the plasma processing system **100** for the radiating antenna **104**. Resonating antenna **600** includes a pair of spiral resonant antennas, each configured as a quarter-wavelength resonator. The first one of the pair of spiral resonant antennas is the first coil **602** (also referred to as the inner coil). A second one of the pair of spiral resonant antennas is the second coil **604** (also referred to as the outer coil). The first coil **602** and the second coil **604** are shown to be substantially on the same plane and nested within each other. The nested arrangement effectively places each turn of the first coil **602** adjacent to a respective turn of the second coil **604**. Each coil **602**, **604** may have one or more turns to form the respective spiral resonant antenna. Thus, the number of turns for each coil **602**, **604** is non-limiting. In embodiments, the current flow path in the resonating antenna **600** is from circuit **300** at terminal **608** to the second coil **604** and from the first coil **602** to circuit **300** at terminal **606**.

In embodiments, the resonating antenna **600** is arranged on a plane parallel to the top cover **105** of the plasma chamber **106**. In embodiments, the resonating antenna **600** is coupled to a mechanical structure **614** (e.g., an actuator) that allows the resonating antenna **600** to be vertically adjusted with respect to the top cover **105** while remaining parallel to the top cover **105**. In embodiments, the matching circuit **103**, the capacitors **304**, **306**, and balun **302** are configurable to provide an improved match based on a change at the load in response to the adjustment of the resonating antenna **600**.

The first coil **602** and the second coil **604** are spiral conductive structures. In embodiments, the electrical lengths of the first coil **602** and the second coil **604** are substantially equal to a quarter resonant frequency wavelength (i.e., quarter-wave). In embodiments, the first coil **602** and the second coil **604** are arranged symmetrically with respect to a center point **622** defining the spiral structure of each coil. In embodiments, the first coil **602** and the second coil **604** are arranged as planar spiral conductive coils. In embodiments, the first coil **602** and the second coil **604** are intertwined on the same plane configured to radiate the electromagnetic wave.

A first end **601** of the first coil **602** and a first end **603** of the second coil **604** are couplable to a reference ground. The first terminal **308** of circuit **300** is couplable to terminal **606** of the first coil **602**, where terminal **606** is at an inner portion of the first coil **602** and at a distance between 1 cm to 10 cm from the first end **601**. The second terminal **310** of circuit **300** is couplable to terminal **608** of the second coil **604**, where terminal **608** is at an inner portion of the second coil **604** and at a distance between 1 cm to 10 cm from the first end **603**. In embodiments, the second end **610** of the first coil **602** and the second end **612** of the second coil **604** are floating (i.e., open circuit), where the second end **610** is at an outer portion of the first coil **602**, and where the second end **612** is at an outer portion of the second coil **604**. In embodiments, the second ends **610**, **612** are couplable to a reference ground.

In embodiments, the first coil **602** and the second coil **604** are arranged in a nested configuration. In embodiments, the first coil **602** and the second coil **604** are arranged in an interwoven (i.e., braided) configuration but electrically isolated. In embodiments, the second coil **604** is arranged such that a radial distance from any point, along the length of the second coil **604**, is equally separated (i.e., equidistance) from the first coil **602**.

In embodiments, the first coil **602** and the second coil **604** are substantially on the same plane. In embodiments, the first coil **602** and the second coil **604** are on different planes that are substantially perpendicular to each other. In embodiments, the first coil **602** and the second coil **604** have a common center point **622** at the center of the spiral conductive structure. In embodiments, the first coil **602** and the second coil **604** are conical coils arranged such that the conical coils have a first common plane at the base and a second common plane at the top. In embodiments, the first coil **602** and the second coil **604** are cylindrical coils arranged such that the cylindrical coils have a first common plane at the base and a second common plane at the top.

In embodiments, the first ends **601** and **603** are substantially on a first plane and 180 degrees offset. In embodiments, the second ends **610** and **612** are substantially on a second plane and 180 degrees offset. In embodiments, the first end **601** is offset from the second end **610** in the first coil **602** such that the electrical length of the first coil **602** corresponds to a quarter resonant frequency wavelength. In embodiments, the first end **603** is offset from the second end **612** in the second coil **604** such that the electrical length of the second coil **604** corresponds to a quarter resonant frequency wavelength. In embodiments, the differential current mode is achieved when the first coil **602** and the second coil **604** are physically connected to RF power at **606** and **608**, respectively, through the current balun (e.g., FIG. **9B**). In embodiments, the first and the second planes are the same planes.

In embodiments, the first coil **602** and the second coil **604** have a design corresponding to an arc or a spiral, for example, an Archimedean, an equiangular, an Euler, a Cornu, a Clothoid, a Cotes, a Fermat, a parabolic, a lituus, a Poinsot, a reciprocal, a hyperbolic, a logarithmic, or a sinusoidal spiral forming a spiral antenna. However, the design of the resonating antenna **600** is non-limiting. As another example, the resonating antenna **600** can be a single-coil arc plate, a double-coil arc plate, or a unibody arc plate.

In embodiments, each of the first coil **602** and the second coil **604** are a solid conductive plate having cutouts to form the respective coils. In embodiments, a non-conductive structure (e.g., a non-conductive plate with cutouts to hold the first coil **602** and the second coil **604**) provides structural support to arrange the first coil **602** within the inner radius of the second coil **604**.

In embodiments, vertical non-conductive structures **630** (e.g., non-conductive offsets perpendicular to the first coil **602** and the second coil **604**) are structurally coupled to the first coil **602** and the second coil **604**. In embodiments, horizontal non-conductive structures **632** provide structural support to separate the first coil **602** from the second coil **604** at an equidistance along the spiral structures. In embodiments, the second ends **610**, **612** of the first coil **602** and the second coil **604**, respectively, are floating. The vertical non-conductive structures **630** and the horizontal non-conductive structures **632** may be arranged on any position along the length of the first coil **602**, the second coil **604**, or both. In embodiments, the vertical non-conductive structures **630** are configurable to vertically adjust the plane on which the resonating antenna **600** is arranged with respect (substantially parallel) to the top cover **105** of the plasma chamber **106**. In embodiments, each of the first coil **602** and the second coil **604** includes a wire arranged in a spiral configuration. The first end of the wire of each of the first coil **602** and the second coil **604** is couplable to a respective terminal (i.e., terminals **308** and **310**) of circuit **300**.

Resonating antenna **600** is arranged as a dual spiral quarter-wavelength resonator, where terminals **606**, **608** of each coil **602**, **604** are couplable to the balun **302**, and a second end **610**, **612** of each coil **602**, **604** is left as an open circuit. A quarter-wavelength resonator exhibits resonance at discrete frequencies corresponding to L (the physical length of each coil **602**, **604**) equal to a multiple of one-quarter of a wavelength (λ) or

$$L = n \times \frac{\lambda}{4},$$

where n is a whole number. Here, the frequency corresponds to the frequency of the RF wave directed from the RF source **102** couplable to the resonating antenna **600**. In embodiments, the physical length of the first coil **602** is substantially equal to that of the second coil **604**. In embodiments, the physical length of the first coil **602** differs from that of the second coil **604**.

Resonating antenna **600**, optionally, includes a third coil **616** nested within a central position in an inner portion of each of the first coil **602** and the second coil **604**. The third coil **616** has a first end **618** and a second end **620** that is grounded. In embodiments, the third coil **616** is substantially on the same plane as the first coil **602**, the second coil **604**, or the first coil **602** and the second coil **604**. In embodiments, the first coil **602**, second coil **604**, and the third coil **616** are symmetrically arranged, such that each coil shares the same center point **622**.

FIG. **7** illustrates an embodiment resonating antenna **700**, which may be arranged in the plasma processing system **100** for the radiating antenna **104**. Resonating antenna **700** includes a pair of spiral resonant antennas, each configured as a quarter-wavelength resonator. The first one of the pair of spiral resonant antennas is the first coil **702** (also referred to as the inner coil). A second one of the pair of spiral resonant antennas is the second coil **704** (also referred to as the outer coil). The first coil **702** and the second coil **704** are shown to be substantially on the same plane. The first coil **702** is nested in a central position within an inner portion of the second coil **704**. Each coil **702**, **704** may have one or more turns to form the respective spiral resonant antenna. Thus, the number of turns for each coil **702**, **704** is non-limiting. In embodiments, the current flow path in the resonating antenna **700** is from circuit **300** at terminal **708** to the second coil **704** and from the first coil **702** to circuit **300** at terminal **706**.

In embodiments, the resonating antenna **700** is arranged on a plane parallel to the top cover **105** of the plasma chamber **106**. In embodiments, the resonating antenna **700** is coupled to a mechanical structure **714** (e.g., an actuator) that allows the resonating antenna **700** to be vertically adjusted with respect to the top cover **105** while remaining parallel to the top cover **105**. In embodiments, the matching circuit **103**, the capacitors **304**, **306**, and balun **302** are configurable to provide an improved match based on a change at the load in response to the adjustment of the resonating antenna **700**.

The first coil **702** and the second coil **704** are spiral conductive structures. In embodiments, the electrical lengths of the first coil **702** and the second coil **704** are substantially equal to a quarter resonant frequency wavelength (i.e., quarter-wave). In embodiments, the first coil **702** and the second coil **704** are arranged symmetrically with respect to a center point **722** defining the spiral structure of each coil. In embodiments, the first coil **702** and the second coil **704** are arranged as planar spiral conductive coils. In embodiments, the first coil **702** and the second coil **704** are on the same plane configured to radiate the electromagnetic wave.

A first end **701** of the first coil **702** and a first end **703** of the second coil **704** are couplable to a reference ground. The first terminal **308** of circuit **300** is couplable to terminal **706** of the first coil **702**, where terminal **706** is at an inner portion of the first coil **702** and at a distance between 1 cm to 10 cm from the first end **701**. The second terminal **310** of circuit **300** is couplable to terminal **708** of the second coil **704**, where terminal **708** is at an inner portion of the second coil **704** and at a distance between 1 cm to 10 cm from the first end **703**. In embodiments, the second end **710** of the first coil **702** and the second end **712** of the second coil **704** are floating (i.e., open circuit), where the second end **710** is at an outer portion of the first coil **702**, and where the second end **712** is at an outer portion of the second coil **704**. In embodiments, the second ends **710**, **712** are couplable to a reference ground.

In embodiments, the first coil **702** and the second coil **704** are arranged in a nested configuration such that the first coil **702** is symmetrically nested within an inner portion of the second coil **704**. In embodiments, the first coil **702** and the second coil **704** are electrically isolated. In embodiments, the second coil **704** is arranged such that a radial distance from any point, along the length of the second coil **704**, is equally separated (i.e., equidistance) from the first coil **702**.

In embodiments, the first coil **702** and the second coil **704** are substantially on the same plane. In embodiments, the first coil **702** and the second coil **704** are on different planes that are substantially perpendicular to each other. In embodiments, the first coil **702** and the second coil **704** have a common center point **722** at the center of the spiral conductive structure. In embodiments, the first coil **702** and the second coil **704** are conical coils arranged such that the conical coils have a first common plane at the base and a second common plane at the top. In embodiments, the first coil **702** and the second coil **704** are cylindrical coils arranged such that the cylindrical coils have a first common plane at the base and a second common plane at the top.

In embodiments, the first ends **701** and **703** are substantially on a first plane and 180 degrees offset. In embodiments, the second ends **710** and **712** are substantially on a second plane and 180 degrees offset. In embodiments, the first end **701** is offset from the second end **710** in the first coil **702** such that the electrical length of the first coil **702** corresponds to a quarter resonant frequency wavelength. In embodiments, the first end **703** is offset from the second end **712** in the second coil **704** such that the electrical length of the second coil **704** corresponds to a quarter resonant frequency wavelength. In embodiments, the differential current mode is achieved when the first coil **702** and the second coil **704** are physically connected to RF power input at **706** and **708**, respectively, through the current balun (e.g., FIG. **9**B). In embodiments, the first and the second planes are the same planes.

In embodiments, the first coil **702** and the second coil **704** have a design corresponding to an arc or a spiral, for example, an Archimedean spiral forming a spiral antenna. However, the design of the resonating antenna **700** is non-limiting. For example, in embodiments, the first coil **702** and the second coil **704** can be in the shape of logarithmic spirals forming a spiral antenna. As another example, the resonating antenna **700** can be a single-coil arc plate, a double-coil arc plate, or a unibody arc plate.

In embodiments, each of the first coil **702** and the second coil **704** are a solid conductive plate having cutouts to form the respective coils. In embodiments, a non-conductive structure (e.g., a non-conductive plate with cutouts to hold the first coil **702** and the second coil **704**) provides structural support to arrange the first coil **702** within the inner radius of the second coil **704**.

In embodiments, vertical non-conductive structures **730** (e.g., non-conductive offsets perpendicular to the first coil **702** and the second coil **704**) are structurally coupled to the first coil **702** and the second coil **704**. In embodiments, horizontal non-conductive structures **732** provide structural support to separate the first coil **702** from the second coil **704** along the spiral structures. In embodiments, the second ends **710**, **712** of the first coil **702** and the second coil **704**, respectively, are floating. The vertical non-conductive structures **730** and the horizontal non-conductive structures **732** may be arranged on any position along the length of the first coil **702**, the second coil **704**, or both. In embodiments, the vertical non-conductive structures **730** are configurable to vertically adjust the plane on which the resonating antenna **700** is arranged with respect (substantially parallel) to the top cover **105** of the plasma chamber **106**. In embodiments, the first coil **702** and the second coil **704** include a wire arranged in a spiral configuration. The first end of the wire of each of the first coil **702** and the second coil **704** is couplable to a respective terminal (i.e., terminals **308** and **310**) of circuit **300**.

Resonating antenna **700** is arranged as a dual spiral quarter-wavelength resonator, where terminals **706**, **708** of each coil **702**, **704** are couplable to the balun **302**, and a second end **710**, **712** of each coil **702**, **704** is left as an open circuit. A quarter-wavelength resonator exhibits resonance at discrete frequencies corresponding to L (the physical length of each coil **702**, **704**) equal to a multiple of one-quarter of a wavelength (λ) or

$$L = n \times \frac{\lambda}{4},$$

where n is a whole number. Here, the frequency corresponds to the frequency of the RF wave directed from the RF source **102** couplable to the resonating antenna **700**. In embodiments, the physical length of the first coil **702** is substantially equal to the physical length of the second coil **704**. In embodiments, the physical length of the first coil **702** is different from that of the second coil **704**.

Resonating antenna **700**, optionally, includes a third coil **716** nested within a central position in an inner portion of each of the first coil **702** and the second coil **704**. The third coil **716** has a first end **718** and a second end **720** that is grounded. In embodiments, the third coil **716** is substantially on the same plane as the first coil **702**, the second coil **704**, or the first coil **702** and the second coil **704**. In embodiments, the first coil **702**, second coil **704**, and the third coil **716** are symmetrically arranged, such that each coil shares the same center point **722**.

FIG. **8**A illustrates an embodiment resonating antenna **800**, which may be arranged in the plasma processing system **100** for the radiating antenna **104**. Resonating antenna **800** includes a pair of conical spiral resonant antennas, each configured as a quarter-wavelength resonator. The first one of the pair of conical spiral resonant antennas is the first coil **802** (also referred to as the inner coil). A second one of the pair of conical spiral resonant antennas is the second coil **804** (also referred to as the outer coil). The first coil **802** and the second coil **804** are nested within each other. The nested arrangement effectively places each turn of the first coil **802** adjacent to a respective turn of the second coil **804**. Each coil **802**, **804** may have one or more turns to form the respective spiral resonant antenna. Thus, the number of turns for each coil **802**, **804** is non-limiting.

In embodiments, the current flow path in the resonating antenna **800** is from circuit **300** at terminal **806** to the first coil **802** and from the second coil **804** to circuit **300** at terminal **808**. In embodiments, the current flow path in the resonating antenna **800** is from circuit **300** at terminal **808** to the second coil **804** and from the first coil **802** to circuit **300** at terminal **806**.

In embodiments, the second ends **810**, **812** are on a first plane **824** that is substantially parallel and nearest (with respect to the resonating antenna **800**) to the top cover **105** of the plasma chamber **106**. In embodiments, the resonating antenna **800** is coupled to a mechanical structure **814** (e.g., an actuator) that allows the resonating antenna **800** to be vertically adjusted with respect to the top cover **105** while the first plane **824** remains parallel to the top cover **105**. In embodiments, the matching circuit **103**, the capacitors **304**, **306**, and balun **302** are configurable to provide an improved match based on a change at the load in response to the adjustment of the resonating antenna **800**.

The first coil **802** and the second coil **804** are spiral conductive structures. In embodiments, the electrical lengths of the first coil **802** and the second coil **804** are substantially equal to a quarter resonant frequency wavelength (i.e., quarter-wave). In embodiments, the first coil **802** and the second coil **804** are arranged symmetrically with respect to a center line **822**, perpendicular to the first plane **824**.

A first end **801** of the first coil **802** and a first end **803** of the second coil **804** are couplable to a reference ground. The first terminal **308** of circuit **300** is couplable to terminal **806** of the first coil **802**, where terminal **806** is at a vertical position further away from first plane **824** than the second end **810** in the first coil **802**. The second terminal **310** of circuit **300** is couplable to terminal **808** of the second coil **804**, where terminal **808** is at a vertical position further away from the first plane **824** than the second end **812** in the second coil. In embodiments, the second end **810** of the first coil **802** and the second end **812** of the second coil **804** are floating (i.e., open circuit), where the second end **810** is vertically nearest to the first plane **824** with respect to terminal **806** in the first coil **802**, and where the second end **812** is vertically nearest to the first plane **824** with respect to terminal **808** in the second coil **804**. In embodiments, the second ends **810**, **812** are couplable to a reference ground.

In embodiments, the first coil **802** and the second coil **804** are arranged in a nested configuration. In embodiments, the first coil **802** and the second coil **804** are electrically isolated. In embodiments, the second coil **804** is arranged such that a radial distance from any point, along the length of the second coil **804**, is equally separated (i.e., equidistance) from the first coil **802**.

In embodiments, the terminals **806**, **808** are on a second plane **826** that is substantially parallel and furthest (with respect to the first plane **824**) to the top cover **105** of the plasma chamber **106**. In embodiments, the first coil **802** and the second coil **804** are conical coils (i.e., the bottom radius of coils **802**, **804** on first plane **824** is different from the top radius of coils **802**, **804** on plane **826**. In embodiments, the coils **802**, **804** are arranged such that the conical coils have a first common plane (i.e., first plane **824**) at the base and a second common plane (i.e., second plane **826**) at the top. In embodiments, the first coil **802** and the second coil **804** are cylindrical coils arranged such that the cylindrical coils have a first common plane at the base (i.e., first plane **824**) and a second common plane (i.e., second plane **826**) at the top.

In embodiments, the first ends **801** and **803** are substantially on a second plane **826** and 180 degrees offset. In embodiments, the second ends **810** and **812** are substantially on a first plane **824** and 180 degrees offset. In embodiments, the first end **801** is offset from the second end **810** in the first coil **802** such that the electrical length of the first coil **802** corresponds to a quarter resonant frequency wavelength. In embodiments, the first end **803** is offset from the second end **812** in the second coil **804** such that the electrical length of the second coil **804** corresponds to a quarter resonant frequency wavelength. In embodiments, the differential current mode is achieved when the first coil **802** and the second coil **804** are physically connected to RF power input at **806** and **808**, respectively, through the current balun (e.g., FIG. 9B). In embodiments, the planes **824**, **826** are offset from each with a distance that results in a quarter-wave electrical length for the first coil **802** and the second coil **804**.

In embodiments, the first coil **802** and the second coil **804** have a design corresponding to a conical arc or a conical spiral, for example, an Archimedean conical spiral forming a conical spiral antenna. However, the design of the resonating antenna **800** is non-limiting. For example, in embodiments, the first coil **802** and the second coil **804** can be in the shape of conical logarithmic spirals forming a conical spiral antenna. As another example, the resonating antenna **800** can be a conical single-coil arc plate, a conical double-coil arc plate, or a conical unibody arc plate.

In embodiments, a non-conductive structure (e.g., a non-conductive plate with cutouts to hold the first coil **802** and the second coil **804**) provides structural support to arrange the first coil **802** within the inner radius of the second coil **804**.

In embodiments, vertical non-conductive structures **830** (e.g., non-conductive offsets perpendicular to the first plane **824** and the second plane **826**) are structurally coupled to the first coil **802** and the second coil **804**. In embodiments, horizontal non-conductive structures **832** provide structural support to separate the first coil **802** from the second coil **804** at an equidistance along the spiral structures. In embodiments, the second ends **810**, **812** of the first coil **802** and the second coil **804**, respectively, are floating. The vertical non-conductive structures **830** and the horizontal non-conductive structures **832** may be arranged on any position along the length of the first coil **802**, the second coil **804**, or both. In embodiments, the vertical non-conductive structures **830** are configurable to vertically adjust the first plane **824** on which the resonating antenna **800** is arranged with respect (substantially parallel) to the top cover **105** of the plasma chamber **106**. In embodiments, the first coil **802** and the second coil **804** include a wire arranged in a spiral configuration. The first end of the wire of each of the first coil **802** and the second coil **804** is couplable to a respective terminal (i.e., terminals **308** and **310**) of circuit **300**.

Resonating antenna **800** is arranged as a conical dual spiral quarter-wavelength resonator, where terminals **806**, **808** of each coil **802**, **804** are couplable to the balun **302**, and a second end **810**, **812** of each coil **802**, **804** is left as an open circuit. A quarter-wavelength resonator exhibits resonance at discrete frequencies corresponding to L (the physical length of each coil **802**, **804**) equal to a multiple of one-quarter of a wavelength (λ) or

$$L = n \times \frac{\lambda}{4},$$

where n is a whole number. Here, the frequency corresponds to the frequency of the RF wave directed from the RF source **102** couplable to the resonating antenna **800**. In embodiments, the physical length of the first coil **802** is substantially equal to the physical length of the second coil **804**. In embodiments, the physical length of the first coil **802** is different from that of the second coil **804**.

FIG. **8**B illustrates an embodiment resonating antenna **850**, which may be arranged in the plasma processing system **100** for the radiating antenna **104**. Resonating antenna **850** includes a pair of conical spiral resonant antennas, each configured as a quarter-wavelength resonator. The first one of the pair of conical spiral resonant antennas is the first coil **852**. A second one of the pair of conical spiral resonant antennas is the second coil **854**. The first coil **852** and the second coil **854** are arranged on a respective plane parallel to the other, but with a vertical offset in the vertical direction with respect to the plasma chamber **106**. Each coil **852**, **854** may have one or more turns to form the respective spiral resonant antenna. Thus, the number of turns for each coil **852**, **854** is non-limiting.

In embodiments, the current flow path in the resonating antenna **850** is from circuit **300** at terminal **856** to the first coil **852** and from the second coil **854** to circuit **300** at terminal **858**. In embodiments, the current flow path in the resonating antenna **850** is from circuit **300** at terminal **858** to the second coil **854** and from the first coil **852** to circuit **300** at terminal **856**.

In embodiments, the first end **851** and the second end **860** are on a first plane **874** that is substantially parallel and nearest (with respect to the resonating antenna **850**) to the top cover **105** of the plasma chamber **106**. In embodiments, the matching circuit **103**, the capacitors **304**, **306**, and balun **302** are configurable to provide an improved match based on a change at the load in response to the adjustment of the resonating antenna **850**.

In embodiments, the first end **853** and the second end **862** are on a second plane **876** that is substantially parallel and furthest (with respect to the resonating antenna **850** and first plane **874**) to the top cover **105** of the plasma chamber **106**. In embodiments, the resonating antenna **850** is coupled to a mechanical structure **864** (e.g., an actuator) that allows the resonating antenna **850** to be vertically adjusted with respect to the top cover **105** while the first plane **874** and second plane **876** remain parallel to the top cover **105**. In embodiments, the matching circuit **103**, the capacitors **304**, **306**, and balun **302** are configurable to provide an improved match based on a change at the load in response to the adjustment of the resonating antenna **850**.

The first coil **852** and the second coil **854** are spiral conductive structures. In embodiments, the electrical lengths of the first coil **852** and the second coil **854** are substantially equal to a quarter resonant frequency wavelength (i.e., quarter-wave). In embodiments, the first coil **852** and the second coil **854** are arranged symmetrically with respect to a center line **872**, perpendicular to the first plane **874**.

A first end **851** of the first coil **852** and a first end **853** of the second coil **854** are couplable to a reference ground. The first terminal **308** of circuit **300** is couplable to terminal **856** of the first coil **852**, where terminal **856** is on the first plane **874**. The second terminal **310** of circuit **300** is couplable to terminal **858** of the second coil **854**, where terminal **858** is on the second plane **876**. In embodiments, the second end **860** of the first coil **852** and the second end **862** of the second coil **854** are floating (i.e., open circuit). In embodiments, the second ends **860**, **862** are couplable to a reference ground.

In embodiments, the first coil **852** and the second coil **854** are arranged in a nested configuration. In embodiments, the first coil **852** and the second coil **854** are electrically isolated. In embodiments, the second coil **854** is arranged such that a radial distance from any point along the length of the second coil **854**, is equally separated (i.e., equidistance) from the first coil **852**.

In embodiments, the first ends **851**, **853** are substantially 180 degrees offset. In embodiments, the second ends **860** and **862** are substantially 180 degrees offset. In embodiments, the first end **851** is offset from the second end **860** in the first coil **852** such that the electrical length of the first coil **852** corresponds to a quarter resonant frequency wavelength. In embodiments, the first end **853** is offset from the second end **862** in the second coil **854** such that the electrical length of the second coil **854** corresponds to a quarter resonant frequency wavelength. In embodiments, the differential current mode is achieved when the first coil **852** and the second coil **854** are physically connected to RF power input at **856** and **858**, respectively, through the current balun (e.g., FIG. **9**B).

In embodiments, the first coil **852** and the second coil **854** have a design corresponding to an arc or a spiral, for example, an Archimedean, an equiangular, an Euler, a Cornu, a Clothoid, a Cotes, a Fermat, a parabolic, a lituus, a Poinsot, a reciprocal, a hyperbolic, a logarithmic, or a sinusoidal spiral forming a spiral antenna. However, the design of the resonating antenna **850** is non-limiting. As another example, the resonating antenna **850** can be a single-coil arc plate, a double-coil arc plate, or a unibody arc plate.

In embodiments, a non-conductive structure (e.g., a non-conductive plate with cutouts to hold the first coil **852** and the second coil **854**) provides structural support to arrange the first coil **852** and the second coil **854**.

In embodiments, vertical non-conductive structures **880** (e.g., non-conductive offsets perpendicular to the first coil **852** and the second coil **854**) are structurally coupled to the first coil **852** and the second coil **854**. In embodiments, horizontal non-conductive structures **882** provide structural support to separate the spirals of each coil at an equidistance along the spiral structures. In embodiments, the second ends **860**, **862** of the first coil **852** and the second coil **854**, respectively, are floating. The vertical non-conductive structures **880** and the horizontal non-conductive structures **882** may be arranged on any position along the length of the first coil **852**, the second coil **854**, or both. In embodiments, the vertical non-conductive structures **880** are configurable to vertically adjust the first plane **874** on which the resonating antenna **850** is arranged with respect (substantially parallel) to the top cover **105** of the plasma chamber **106**. In embodiments, each of the first coil **852** and the second coil **854** includes a wire arranged in a spiral configuration. The first end of the wire of each of the first coil **852** and the second coil **854** is couplable to a respective terminal (i.e., terminals **308** and **310**) of circuit **300**.

Resonating antenna **850** is arranged as a dual spiral quarter-wavelength resonator, where terminals **856**, **858** of each coil **852**, **854** are couplable to the balun **302**, and a second end **860**, **862** of each coil **852**, **854** is left as an open circuit. A quarter-wavelength resonator exhibits resonance at discrete frequencies corresponding to L (the physical length of each coil **852**, **854**) equal to a multiple of one-quarter of a wavelength (λ) or

$$L = n \times \frac{\lambda}{4},$$

where n is a whole number.

Here, the frequency corresponds to the frequency of the RF wave directed from the RF source **102** couplable to the resonating antenna **850**. In embodiments, the physical length of the first coil **852** is substantially equal to the physical length of the second coil **854**. In other embodiments, the physical length of the first coil **852** is different from the physical length of the second coil **854**.

In the various embodiments of FIGS. **4-8**B, the resonating antenna is advantageously configured to operate with only a single RF source. Each respective resonating antenna includes dual spiral single-pole antennas having a first inner ring nested adjacent and within a second outer ring. Each of the dual spiral single-pole antennas operates as a quarter-wavelength resonator. In these embodiments, the balanced design of the feed and resonating structure introduces maxima voltages at the inner coil sections. Further, in these embodiments, the inner coil section is 180 degrees out of phase from the outer coil section. Advantageously, the embodiments of this disclosure provide balanced currents to the resonating antennas, which improves plasma uniformity within the plasma chamber **106**. Moreover, the dimensions, structure, and material of the third coil, nested within the first and second spiral resonant antennas for each resonating antenna, is selected (i.e., tuned) based on the different arrangements of the dual spiral resonant antennas in each configuration of the resonating antenna disclosed herein.

FIG. **9**A illustrates a schematic of an embodiment voltage balun transformer **900**, which may be arranged as the balun **302** in circuit **300**. The voltage balun transformer **900** includes a first winding **901** and a second winding **903**. In embodiments, first winding **901** includes a first coil **902**, and second winding **903** includes a second coil **904** and a third coil **906**. A first unbalanced terminal **908** and a second unbalanced terminal **910** of the voltage balun transformer **900**, at the ends of the first coil **902**, are couplable to the matching circuit **103** at terminals **316** and **318** of circuit **300**. Second coil **904** and third coil **906** are couplable to the radiating antenna **104** at balanced terminals **912** and **914**, respectively. In embodiments, one of the unbalanced terminals **908** or **910** is coupled to a reference ground.

In embodiments, the first coil **902** has the same number of turns as the combined number of turns in the second coil **904** and the third coil **906**. In embodiments, the second coil **904** and the third coil **906** have the same number of turns. In embodiments, the second coil **904** and the third coil **906** share an iron core. As shown, the shared node **916** between the second coil **904** and the third coil **906** is coupled to the reference ground. However, it should be understood that the shared node **916**, in embodiments, may also be floating.

FIG. **9**B illustrates a schematic of an embodiment current balun transformer **930**, which may be arranged as the balun **302** in circuit **300**. The current balun transformer **930** includes a first winding **931** and a second winding **933**. In embodiments, first winding **931** includes a first coil **932** and the second winding **933** includes a second coil **934**. A first unbalanced terminal **940** and a second unbalanced terminal **942** of the current balun transformer **930** at the ends of the first coil **932** and the second coil **934**, respectively, are couplable to the matching circuit **103** at terminals **316** and **318** of circuit **300**. The first coil **932** and the second coil **934** are couplable to the radiating antenna **104** at balanced terminals **936** and **938**, respectively. In embodiments, one of the unbalanced terminals **940** or **942** is coupled to a reference ground. In embodiments, the first coil **932** has the same number of turns as the second coil **934**.

FIG. **10** illustrates a block diagram of an embodiment processing system **1000**, which may be coupled to the plasma processing system **100**. As shown, the processing system **1000** includes a processor **1002**, a memory **1004**, an interface **1006**, an optional feedback circuit **1008**, and an optional measurement circuit **1010**, which may (or may not) be arranged as shown. The processing system **1000** may include additional components not depicted, such as long-term storage (e.g., non-volatile memory, etc.), measurement devices, and the like. Although the processing system **1000** is shown to have one of each component (i.e., the processor **1002**, the memory **1004**, etc.), the number of components is not limiting and greater numbers are similarly contemplated in other embodiments. In such embodiments, the task performed by the component disclosed herein may be spread through these additional components.

Processor **1002** may be any component or collection of components adapted to perform computations or other processing-related tasks. Memory **1004** may be any component or collection of components adapted to store programming or instructions for execution by the processor **1002**. In an embodiment, memory **1004** includes a non-transitory computer-readable medium.

Interface **1006** may be any component or collection of components that allow the processor **1002** to communicate with other devices/components or a user. For example, interface **1006** may be adapted to communicate data, control, or management messages from processor **1002** to a structure or circuit coupled to an actuator to adjust the vertical position of the radiating antenna **104** with respect to the plasma chamber or to adjust the configuration of the matching circuit **103**, balun **302**, or capacitors **304**, **306** based on instructions or configurations stored in memory **1004**. As another example, interface **1006** may be adapted to allow a user or device (e.g., personal computer (PC), etc.) to interact/communicate with the processing system **1000**.

The feedback circuit **1008** may be used to receive measurements from the measurement circuit **1010** to automatically or manually change, through processor **1002**, the configuration of the matching circuit **103**, balun **302**, or capacitors **304**, **306** in the plasma processing system **100**. The measurement circuit **1010** may be used to measure, for example, the plasma stability, pressure, ignition stability, density, or the like.

A first aspect relates to a plasma processing system. The plasma processing system includes a plasma chamber, an RF source, a matching circuit, a balun, and a resonating antenna. The RF source is configured to generate a forward RF wave. The matching circuit is coupled to the RF source and is configured to provide matching for the RF source. The balun includes unbalanced terminals coupled to the matching circuit. The resonating antenna is configured to generate plasma within the plasma chamber and includes a first spiral resonant antenna and a second spiral resonant antenna. The first spiral resonant antenna has an electrical length corresponding to a quarter of a wavelength of a frequency of the forward RF wave, a first end and a second end. The first end is coupled to a first balanced terminal of the balun and the second end is an open circuit. The second spiral resonant antenna has an electrical length corresponding to a quarter of the wavelength of the frequency of the forward RF wave, a first end and a second end. The first end is coupled to a second balanced terminal of the balun and the second end is an open circuit. The first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having the same center point.

In a first implementation form of the plasma processing system, according to the first aspect as such, the first end of the first spiral resonant antenna and the first end of the second spiral resonant antenna are arranged 180 degrees with respect to the center point.

In a second implementation form of the plasma processing system, according to the first aspect as such or any preceding implementation of the first aspect, the first spiral resonant antenna is 180 degrees out of phase from the second spiral resonant antenna.

In a third implementation form of the plasma processing system, according to the first aspect as such or any preceding implementation of the first aspect, an entirety of the first spiral resonant antenna is arranged within an interior portion of the second spiral resonant antenna.

In a fourth implementation form of the plasma processing system, according to the first aspect as such or any preceding implementation of the first aspect, the first end of the first spiral resonant antenna and the first end of the second spiral resonant antenna are on a first plane. The second end of the first spiral resonant antenna and the second end of the second spiral resonant antenna are on a second plane different from the first plane.

In a fifth implementation form of the plasma processing system, according to the first aspect as such or any preceding implementation of the first aspect, the resonating antenna further includes a coil symmetrically nested within an interior portion of the first spiral resonant antenna and an interior portion of the second spiral resonant antenna. The coil's first and second ends are coupled to RF ground.

In a sixth implementation form of the plasma processing system, according to the first aspect as such or any preceding implementation of the first aspect, the balun is a voltage balun transformer or a current balun transformer.

A second aspect relates to a resonating antenna for generating plasma within a plasma chamber. The resonating antenna includes a first spiral resonant antenna having an electrical length corresponding to a quarter of a wavelength of a frequency of a forward RF wave fed by an RF source couplable to the resonating antenna. The first spiral resonant antenna has a first end and a second end. The first end couplable to a first balanced terminal of a balun and the second end is an open circuit. The second spiral resonant antenna has an electrical length corresponding to a quarter of the wavelength of the frequency of the forward RF wave. The second spiral resonant antenna has a first and second end, the first end couplable to a second balanced terminal of the balun and the second end is an open circuit. The first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having the same center point.

In a first implementation form of the resonating antenna, according to the second aspect as such, the first spiral resonant antenna and the second spiral resonant antenna are arranged in a braided configuration.

In a second implementation form of the resonating antenna, according to the second aspect as such or any preceding implementation of the second aspect, the first spiral resonant antenna is 180 degrees out of phase from the second spiral resonant antenna.

In a third implementation form of the resonating antenna, according to the second aspect as such or any preceding implementation of the second aspect, an entirety of the first spiral resonant antenna is arranged within an interior portion of the second spiral resonant antenna.

In a fourth implementation form of the resonating antenna, according to the second aspect as such or any preceding implementation of the second aspect, the first end of the first spiral resonant antenna and the first end of the second spiral resonant antenna are on a first plane. The second end of the first spiral resonant antenna and the second end of the second spiral resonant antenna are on a second plane different from the first plane.

In a fifth implementation form of the resonating antenna, according to the second aspect as such or any preceding implementation of the second aspect, the resonating antenna further includes a coil symmetrically nested within an interior portion of the first spiral resonant antenna and an interior portion of the second spiral resonant antenna. The coil's first and second ends are coupled to RF ground.

In a sixth implementation form of the resonating antenna, according to the second aspect as such or any preceding implementation of the second aspect, the first end of the first spiral resonant antenna is an end of the first spiral resonant antenna nearest to the center point. The first end of the second spiral resonant antenna is the end of the second spiral resonant antenna nearest to the center point.

A third aspect relates to an apparatus for generating plasma in a plasma chamber of a plasma processing system. The apparatus includes an RF source configured to generate a forward RF wave; a matching circuit coupled to the RF source, the matching circuit configured to provide matching for the RF source; a balun having unbalanced terminals coupled to the matching circuit; a resonating antenna, the resonating antenna configured to generate plasma within the plasma chamber, the resonating antenna having: a first spiral resonant antenna having an electrical length corresponding to a quarter of a wavelength of a frequency of the forward RF wave, the first spiral resonant antenna having a first end and a second end, the first end coupled to a first balanced terminal of the balun and the second end that is open circuit, and

a second spiral resonant antenna having an electrical length corresponding to the quarter of the wavelength of the frequency of the forward RF wave, the second spiral resonant antenna having a first end and a second end, the first end coupled to a second balanced terminal of the balun and the second end that is open circuit, wherein the first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having a same center point; a non-transitory memory storage comprising instructions; and a processor in communication with the non-transitory memory storage and coupled to the matching circuit, wherein the instructions, when executed by the processor, cause the processor to provide a matching impedance between the RF source and the resonating antenna.

In a first implementation form of the apparatus, according to the third aspect as such, the first spiral resonant antenna is 180 degrees out of phase from the second spiral resonant antenna.

In a second implementation form of the apparatus, according to the third aspect as such or any preceding implementation of the third aspect, an entirety of the first spiral resonant antenna is arranged within an interior portion of the second spiral resonant antenna.

In a third implementation form of the apparatus, according to the third aspect as such or any preceding implementation of the third aspect, the first end of the first spiral resonant antenna and the first end of the second spiral resonant antenna are on a first plane. The second end of the first spiral resonant antenna and the second end of the second spiral resonant antenna are on a second plane different from the first plane.

In a fourth implementation form of the apparatus, according to the third aspect as such or any preceding implementation of the third aspect, the resonating antenna further includes a coil symmetrically nested within an interior portion of the first spiral resonant antenna and an interior portion of the second spiral resonant antenna. The coil's first and second ends are coupled to RF ground.

In a fifth implementation form of the apparatus, according to the third aspect as such or any preceding implementation of the third aspect, the balun is a voltage balun transformer or a current balun transformer.

It is noted that all steps outlined in the disclosure are not necessarily required and can be optional. Further, changes to the arrangement of the steps, removal of one or more steps and path connections, and addition of steps and path connections are similarly contemplated.

Although the description has been described in detail, it should be understood that various changes, substitutions, and alterations may be made without departing from the spirit and scope of this disclosure as defined by the appended claims. The same elements are designated with the same reference numbers in the various figures. Moreover, the scope of the disclosure is not intended to be limited to the particular embodiments described herein, as one of ordinary skill in the art will readily appreciate from this disclosure that processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed, may perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

The specification and drawings are, accordingly, to be regarded simply as an illustration of the disclosure as defined by the appended claims, and are contemplated to cover any and all modifications, variations, combinations, or equivalents that fall within the scope of the present disclosure.

What is claimed is:

1. A plasma processing system, comprising:
- a plasma chamber;
- an RF source configured to generate a forward RF wave;
- a matching circuit coupled to the RF source, the matching circuit configured to provide matching for the RF source;
- a balun having unbalanced terminals coupled to the matching circuit; and
- a resonating antenna, the resonating antenna configured to generate plasma within the plasma chamber, the resonating antenna having:
  - a first spiral resonant antenna having an electrical length corresponding to a quarter of a wavelength of a frequency of the forward RF wave, the first spiral resonant antenna having a first end and a second end, the first end coupled to a first balanced terminal of the balun and the second end that is open circuit, and
  - a second spiral resonant antenna having an electrical length corresponding to the quarter of the wavelength of the frequency of the forward RF wave, the second spiral resonant antenna having a first end and a second end, the first end coupled to a second balanced terminal of the balun and the second end that is open circuit, wherein the first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having a same center point.

2. The plasma processing system of claim 1, wherein the first end of the first spiral resonant antenna and the first end of the second spiral resonant antenna are arranged 180 degrees with respect to the center point.

3. The plasma processing system of claim 1, wherein the first spiral resonant antenna is 180 degrees out of phase from the second spiral resonant antenna.

4. The plasma processing system of claim 1, wherein an entirety of the first spiral resonant antenna is arranged within an interior portion of the second spiral resonant antenna.

5. The plasma processing system of claim 1, wherein the first end of the first spiral resonant antenna and the first end of the second spiral resonant antenna are on a first plane, and wherein the second end of the first spiral resonant antenna and the second end of the second spiral resonant antenna are on a second plane different from the first plane.

6. The plasma processing system of claim 1, wherein the resonating antenna further includes a coil symmetrically nested within an interior portion of the first spiral resonant antenna and an interior portion of the second spiral resonant antenna, and wherein a first end and a second end of the coil are coupled to RF ground.

7. The plasma processing system of claim 1, wherein the balun is a voltage balun transformer or a current balun transformer.

8. A resonating antenna for generating plasma within a plasma chamber, the resonating antenna comprising:
- a first spiral resonant antenna having an electrical length corresponding to a quarter of a wavelength of a frequency of a forward RF wave fed by an RF source couplable to the resonating antenna, the first spiral resonant antenna having a first end and a second end, the first end couplable to a first balanced terminal of a balun and the second end that is open circuit, and
- a second spiral resonant antenna having an electrical length corresponding to the quarter of the wavelength, the second spiral resonant antenna having a first end and a second end, the first end couplable to a second balanced terminal of the balun and the second end that is open circuit, wherein the first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having a same center point.

9. The resonating antenna of claim 8, wherein the first spiral resonant antenna and the second spiral resonant antenna are arranged in a braided configuration.

10. The resonating antenna of claim 8, wherein the first spiral resonant antenna is 180 degrees out of phase from the second spiral resonant antenna.

11. The resonating antenna of claim 8, wherein an entirety of the first spiral resonant antenna is arranged within an interior portion of the second spiral resonant antenna.

12. The resonating antenna of claim 8, wherein the first end of the first spiral resonant antenna and the first end of the second spiral resonant antenna are on a first plane, and wherein the second end of the first spiral resonant antenna and the second end of the second spiral resonant antenna are on a second plane different from the first plane.

13. The resonating antenna of claim 8, further comprising a coil symmetrically nested within an interior portion of the first spiral resonant antenna and an interior portion of the

second spiral resonant antenna, and wherein a first end and a second end of the coil are coupled to RF ground.

14. The resonating antenna of claim **8**, wherein the first end of the first spiral resonant antenna is an end of the first spiral resonant antenna nearest to the center point, and wherein the first end of the second spiral resonant antenna is an end of the second spiral resonant antenna nearest to the center point.

15. An apparatus for generating plasma in a plasma chamber of a plasma processing system, the apparatus comprising:

an RF source configured to generate a forward RF wave;

a matching circuit coupled to the RF source, the matching circuit configured to provide matching for the RF source;

a balun having unbalanced terminals coupled to the matching circuit;

a resonating antenna, the resonating antenna configured to generate plasma within the plasma chamber, the resonating antenna having:

a first spiral resonant antenna having an electrical length corresponding to a quarter of a wavelength of a frequency of the forward RF wave, the first spiral resonant antenna having a first end and a second end, the first end coupled to a first balanced terminal of the balun and the second end that is open circuit, and

a second spiral resonant antenna having an electrical length corresponding to the quarter of the wavelength of the frequency of the forward RF wave, the second spiral resonant antenna having a first end and a second end, the first end coupled to a second balanced terminal of the balun and the second end that is open circuit, wherein the first spiral resonant antenna and the second spiral resonant antenna are arranged in a symmetrically nested configuration having a same center point;

a non-transitory memory storage comprising instructions; and

a processor in communication with the non-transitory memory storage and coupled to the matching circuit, wherein the instructions, when executed by the processor, cause the processor to provide a matching impedance between the RF source and the resonating antenna.

16. The apparatus of claim **15**, wherein the first spiral resonant antenna is 180 degrees out of phase from the second spiral resonant antenna.

17. The apparatus of claim **15**, wherein an entirety of the first spiral resonant antenna is arranged within an interior portion of the second spiral resonant antenna.

18. The apparatus of claim **15**, wherein the first end of the first spiral resonant antenna and the first end of the second spiral resonant antenna are on a first plane, and wherein the second end of the first spiral resonant antenna and the second end of the second spiral resonant antenna are on a second plane different from the first plane.

19. The apparatus of claim **15**, wherein the resonating antenna further includes a coil symmetrically nested within an interior portion of the first spiral resonant antenna and an interior portion of the second spiral resonant antenna, and wherein a first end and a second end of the coil are coupled to RF ground.

20. The apparatus of claim **15**, wherein the balun is a voltage balun transformer or a current balun transformer.

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