RESONANT PHASE-CONTROLLED OSCILLATOR

CROSS REFERENCE TO RELATED PATENTS AND APPLICATIONS

[0001] The present application claims the benefit of U.S. Nonprovisional Application No. 18/589,071 filed on February 27, 2024, which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] The present invention relates generally to radio frequency power circuits, and, in particular embodiments, to systems, apparatuses, and methods for radio frequency power circuits that include a resonant phase-controlled oscillator circuit.

BACKGROUND

[0003] Alternating current (AC) power sources (also known as AC power supplies) are designed to provide AC power to a load (such as an antenna or an electronic device) that alternates between a positive and a negative current at a desired frequency. While many AC power sources operate at relatively low frequencies, such as 50–60 Hz, AC power sources may also produce AC power at much higher frequencies. For example, one particular category of AC power source is a radio frequency (RF) power source, which produces AC power at a frequency in the RF portion of the electromagnetic spectrum, from about 20 kHz to about 300 GHz (RF power). A wide variety of electronic devices make use of RF power, such as communications equipment and industrial processing equipment.

[0004] Efficiently delivery of AC power, such as RF power, to a load can be difficult. For example, the load may include various components, discontinuities, structural features, etc. that can reflect some or all of the power back to the AC power source. The reflected power may then combine with the transmitted power to form standing waves. The difference between the total

AC power provided by the AC power source and the net AC power delivered to the load may then be lost (e.g., due to component and circuit heating). To avoid this, the structure and circuitry of the load can be designed to minimize reflected power (e.g., by matching input and output impedance), such as at a particular frequency. For certain circuits, AC power coupling efficiency can be maximized when the AC power is delivered at a resonant frequency of the AC system where almost all of the delivered AC power is transmitted.

[0005] However, it is not always possible to deliver AC power at the resonant frequency. This is particularly true when the resonant frequency changes (e.g., because the impedance of the load changes) while the AC power is being delivered to the load. One way to adapt to changing impedance is to use adjustable (tunable) impedance matching circuits. Another way is to change the frequency of the AC power as the resonant frequency changes. Yet conventional solutions for both of these methods are relatively slow and are therefore unsuitable for AC systems where the resonant frequency of the load is rapidly changing.

[0006] One specific application where RF power sources are used is to provide RF power to semiconductor processing tools. For example, semiconductor processing tools may couple RF power to a process gas in order to generate plasma in a processing chamber. The plasma may be used to perform or enhance various semiconductor fabrication processes, such as deposition, etching, and others. When RF power is coupled to a processing chamber with no plasma, the processing chamber and associated structures designed to generate the plasma (e.g., antenna, source electrode, etc.) have a certain resonant frequency. Because plasma includes charge carriers (positive and negative species), the presence of the plasma in the processing chamber changes the resonant frequency and the efficiency of the RF power delivery is reduced.

[0007] Additionally, many plasma systems are pulsed plasma systems that deliver RF power to the processing chamber as a series of RF pulses, often inducing changes to the plasma properties that occur at timescales much faster than conventional solutions can adjust. This problem is compounded by the fact that the resonant frequency changes during each pulse, which meaning that problem persists throughout the entire pulsing process. That is, conventional solutions are unable to adjust the frequency of the applied RF power and/or the impedance of the circuit fast enough and are consequently unable to ever efficiently deliver RF power because the properties of the plasma, and hence the load impedance, are continually changing during the RF pulse. Moreover, this deficiency is present in any AC system where the resonant frequency of the load changes rapidly.

SUMMARY

[0008] In accordance with and embodiment of the invention, a resonant oscillator circuit includes an amplifier that includes a control input and a power output configured to deliver radio frequency (RF) power to a resonant load, and a feedback circuit. The feedback circuit includes a sensor coupled to the RF power, and a phase shifter coupled between the control input and the sensor. The sensor is configured to generate a feedback signal using the RF power. The phase shifter is configured to adjust a phase of the feedback signal to provide a conditioned feedback signal at the control input.

[0009] In accordance with another embodiment of the invention, an RF system includes a resonant oscillator circuit that includes an amplifier with a control input and a power output configured to deliver RF power to a resonant load. The resonant oscillator circuit also includes a feedback circuit that includes a sensor coupled to the RF power, and a phase shifter coupled between the control input and the sensor. The sensor is configured to generate a feedback signal

using the RF power. The RF system also includes a controller operatively coupled to the sensor and the phase shifter. The controller is configured to control the phase shifter to adjust a phase of the feedback signal according to a sensor signal received from the sensor to provide a conditioned feedback signal at the control input.

[0010] In accordance with still another embodiment of the invention, a plasma system includes a plasma chamber, an RF structure configured to generate a plasma in the plasma chamber using RF power, a resonant load, a transistor, a direct current (DC) power supply, and a feedback circuit. The resonant load includes the RF structure, the plasma chamber, and the plasma. The transistor includes a control input, a power input, and a power output configured to deliver the RF power to the resonant load. The DC power supply is coupled to the power input of the transistor. The feedback circuit includes a sensor coupled to the RF power, and a phase shifter coupled between the control input and the sensor. The sensor is configured to generate a feedback signal using the RF power. The phase shifter is configured to adjust a phase of the feedback signal to provide a conditioned feedback signal at the control input.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0012] FIG. 1 illustrates an example resonant oscillator circuit that includes a feedback circuit with a sensor coupled to RF power delivered at a power output of an amplifier and a phase shifter coupled between the sensor and a control input of the amplifier in accordance with embodiments of the invention;

[0013] FIG. 2 illustrates an example resonant oscillator circuit that includes a feedback circuit with both a phase shifter and an amplitude regulator in accordance with embodiments of the invention;

[0014] FIG. 3 illustrates an example resonant oscillator circuit that includes an amplifier with a DC power source coupled to a power input of a transistor through an RF choke as well as an optional DC bias and one or more optional impedance transformers in accordance with embodiments of the invention;

[0015] FIG. 4 illustrates an example resonant oscillator circuit that includes a feedback circuit with a sensor that is attached to a resonant load in accordance with embodiments of the invention;

[0016] FIG. 5 illustrates an example resonant oscillator circuit that includes a feedback circuit with a first sensor that is coupled in series with a transmission line between the power output of an amplifier and a resonant load as well as a second sensor that is attached to the resonant load in accordance with embodiments of the invention;

[0017] FIG. 6 illustrates an example RF system that includes a resonant oscillator circuit and a controller configured to send a phase control signal to a phase shifter of a feedback circuit of the resonant oscillator circuit and to receive a sensor signal from a sensor of the feedback circuit in accordance with embodiments of the invention;

[0018] FIG. 7 illustrates an example RF system that includes a resonant oscillator circuit and a controller configured to send an amplitude control signal to an amplitude regulator of a feedback circuit of the resonant oscillator circuit and to receive a sensor signal from a sensor of the feedback circuit in accordance with embodiments of the invention;

[0019] FIG. 8 illustrates an example RF system that includes a resonant oscillator circuit and a controller configured to send various control signals to components of an amplifier of the resonant oscillator circuit and to receive a sensor signal from a sensor of a feedback circuit of the resonant oscillator circuit in accordance with embodiments of the invention;

[0020] FIG. 9 illustrates an example plasma system that includes a feedback circuit coupled to RF power delivered to a resonant load that includes a plasma chamber, an RF structure configured to generate a plasma in the plasma chamber using the RF power, and the plasma where the feedback circuit includes a phase shifter in accordance with embodiments of the invention;

[0021] FIG. 10 illustrates an example plasma system where the RF structure is implemented as an upper electrode of a capacitively coupled plasma (CCP) plasma system in accordance with embodiments of the invention;

[0022] FIG. 11 illustrates an example plasma system where the RF structure is implemented as an RF antenna of an inductively coupled plasma (ICP) plasma system in accordance with embodiments of the invention; and

[0023] FIG. 12 illustrates an example method of adjusting the frequency of RF power applied to a resonant load in accordance with embodiments of the invention.

[0024] Corresponding numerals and symbols in the different figures generally refer to corresponding parts unless otherwise indicated. The figures are drawn to clearly illustrate the relevant aspects of the embodiments and are not necessarily drawn to scale. The edges of features drawn in the figures do not necessarily indicate the termination of the extent of the feature.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0025] The making and using of various embodiments are discussed in detail below. It should be appreciated, however, that the various embodiments described herein are applicable in a wide variety of specific contexts. The specific embodiments discussed are merely illustrative of specific ways to make and use various embodiments, and should not be construed in a limited scope. Unless specified otherwise, the expressions "around", "approximately", and "substantially" signify within 10%, and preferably within 5% of the given value or, such as in the case of substantially zero, less than 10% and preferably less than 5% of a comparable quantity.

[0026] AC power sources, such as RF power sources, are used to supply AC power in a wide variety of applications including power distribution, communications equipment, industrial processing equipment, and others. One example of an application where RF power sources may be used is to supply RF power to a semiconductor processing tool. For example, an RF power source may be configured to couple RF power to a processing gas in order to generate plasma in a processing chamber of a semiconductor processing tool. The plasma can then be used to perform or enhance various semiconductor fabrication processes, such as deposition, etching, and others.

[0027] RF power may be delivered from an RF power source in the form of electromagnetic waves which propagate along a transmission line through RF elements and excite an antenna structure. The antenna structure may be configured to couple the RF power to some region or component of the system, such as plasma in a processing chamber, for example. The term antenna may be broadly understood in this context to be any structure designed to couple the RF power to another part of the system, and of course includes more specific definition of an

antenna. The RF elements may include passive elements, such as capacitors and inductors, but can also include other elements including active elements in some cases.

[0028] Regardless of the specific application, efficient coupling of AC power (e.g., RF power) is desirable. For example, in a given AC circuit, some portion of the propagating electromagnetic waves may be reflected at various points in the AC circuit (i.e., dividing the electromagnetic waves from the total applied power into reflected waves and transmitted waves in some proportion). Such reflections often return power to the AC power source where it is dissipated as heat. That is, the reflected waves end up back at the AC power supply rather than continuing through the AC circuit. This is an undesirable result because more AC power must be delivered in order to couple the desired amount of power. Therefore, it is desirable to design AC systems so that the number and magnitude of reflections in the AC circuit are reduced.

[0029] While the difficulties in efficiently coupling AC power to a system apply to any resonant load that is changing rapidly in time (e.g., relative to the adjustment capabilities of the AC system), one specific example of such a rapidly changing resonant load is a semiconductor processing tool that employs pulsed RF power to generate plasma. For instance, the pulsed RF power may be delivered to a system with varying pulse amplitude, pulse frequency (i.e., the rate that the RF pulses are of repeated, in contrast to the RF frequency of the RF power itself), and duty cycle (the duration that the RF power is on within each pulse repetition period). Such RF power pulses produce repetitive transients in all plasma related quantities. Since the plasma forms an integral part of the RF circuit, a changing plasma presents a changing impedance to the RF system and can lead to increases in the reflected waves above an optimal configuration.

[0030] In the case that the plasma changes over time, in the absence of adjustments to the RF circuit, the RF power that is reflected from the load increases resulting in inconsistent power

delivery to the plasma and/or dissipation of power as heat, such as in transistors (i.e., some of the delivered power is lost rather than coupled to the plasma). One conventional method of mitigating the fluctuations in reflected waves is to adjust the RF circuit as the impedance changes (e.g., by adjusting the frequency or by mechanically moving elements in the RF circuit). Clearly, the ability of such adjustments to prevent reflections is impacted by the speed that the adjustments are made. Specifically, the quicker the RF circuit is adjusted to match the changing impedance, the lower the reflected power will be. For pulsed plasma systems, the plasma is continuously changing. Therefore, adjustments need to be made on a timescale that is shorter than the timescale that the plasma changes (e.g., on the order of microseconds, such as about a 10 μs timescale, or about a 2 μs timescales, or even lower).

[0031] However, conventional mechanical adjustments are too slow to adjust to rapidly changing resonant loads, such as pulsed RF power. For example, RF pulse widths may be in the tens of microseconds, which, in the specific case of pulsed plasma systems, may cause changes to the plasma a 10 μs timescale (or lower). Yet, conventional mechanical adjustments are limited to ten to a hundred millisecond timescales. While conventionally adjusting the frequency of the RF power may be performed more quickly than mechanical adjustments, frequency adjustments are still limited to hundreds of microseconds which is at least an order of magnitude slower than short RF pulse widths and the timescale at which the plasma changes.

[0032] Therefore, an improved RF circuit, apparatus, and method that reduces the time necessary to optimize the power delivered to a resonant load is desirable. For example, it is desirable to quickly minimize reflected power so that RF power can be efficiently delivered to resonant loads that change rapidly in time (e.g., on the timescale of 10 μs, or about 2 μs or even faster).

[0033] In accordance with various embodiments herein described, the invention proposes a phase-controlled resonant oscillator that may be incorporated into an AC circuit (e.g., an RF circuit) coupled to a resonant load (e.g., including a resonant structure or a non-resonant structure that is part of a resonant RF circuit). One or more sensors in the AC circuit generate a feedback signal that may be used to adjust a base frequency of a control signal applied to a control input of an amplifier. The feedback signal is a function of the waveform of an output of the amplifier. The control signal is adjusted in order to match the resonant frequency of the resonant load, which may change (e.g., a rapidly changing resonant load, such as a pulsed RF system). Specifically, properties of the feedback signal, such as phase (e.g., using a phase shifter) and/or amplitude (e.g., with an amplitude regulator), and others, are adjusted to generate a conditioned feedback signal that is then provided as the control signal to the control input of the amplifier.

[0034] Various aspects of the feedback signal, such as the phase of the feedback signal, may be used to determine the base frequency. The amplifier may include an active element, such as a power transistor, and the base frequency may be applied to a control node of the active element, such as the gate of the power transistor. A direct current (DC) current source may be coupled to an input of the active element (e.g., a DC power supply electrically connected to the active element through an RF choke) and the control signal may be applied to the control node to control the flow of current through the active element (i.e., the control signal is related to the output of the active element, an example of which is the gate voltage of a power transistor being related to the drain current of the power transistor, or the DC power supply voltage that relates to the power delivered to the load). In various embodiments, the feedback signal is obtained using

analog circuitry, which may have the advantage of enabling very fast adjustment of the base frequency (e.g., on the order of microseconds, or even faster).

[0035] A variety of conventional oscillator circuits have been designed to provide RF power to a load. However, conventional oscillator circuits typically use crystal oscillators (such as a quartz oscillator) and often do not include a feedback circuit. On the other hand, some conventional oscillator circuits do include a feedback circuit (sometimes referred to as feedback oscillator circuits). Feedback circuits with the ability to detect properties of the RF signal (such as relative phase of transmitted and reflected signals as well as their respective amplitudes) have been included in conventional RF power sources to allow impedance matching networks to respond to fluctuations in the impedance of a load. These conventional feedback circuits are unable to adjust quickly enough to efficiently couple power to rapidly changing loads. For example, conventional feedback circuits do not include various adjustment mechanisms present in the embodiment resonant oscillators described herein, such as a phase-shifter or an amplitude regulator.

[0036] The resonant oscillators described herein may be part of any AC circuit in an AC power source (e.g., an RF circuit in an RF power source) to advantageously reduce the necessary time to optimize delivery of RF power to a resonant load, such as a resonant load that changes rapidly in time. One particular area where the resonant oscillator may provide benefits are in pulsed RF systems due to rapid and repeated impedance transients. Pulsed RF systems are often used in semiconductor plasma systems and increasingly so in recent years. Conventional pulsed RF systems can adjust RF frequency on timescales of hundreds of microseconds and can adjust mechanical RF circuit elements on ten to a hundred millisecond timescales. Thus, during a portion of the pulse (which may be the entire pulse for many pulsed RF systems that use short

pulses) the RF power delivery is not optimized and RF power is not coupled efficiently to the plasma. The resonant oscillators described herein may be advantageously utilized to optimize power delivery in any AC system with a resonant load that changes rapidly in time, such as virtually every application in the semiconductor industry that uses pulsed RF power.

[0037] It should also be noted that although conventional RF systems often utilize some combination of adjusting the frequency and mechanically adjusting RF circuit elements (e.g., mechanically adjustable capacitors), other adjustments, such as electrical adjustments could be possible. However, it can be difficult or impossible to achieve matching using electrical adjustments that is both accurate and affordable. Moreover, even advanced electrical adjustments may still operate on much longer timescales than tens of microseconds. The resonant oscillators described herein may advantageously allow for the compensation of the rapidly changing impedance at appropriately short timescales with low cost and complexity.

[0038] Additionally, instability is often encountered with resonant loads. For example, in the case of plasma systems, instability might arise from non-linear coupling of the RF waves and the plasma. In certain circumstances a positive feedback cycle may occur where a small decrease in the plasma density results in a corresponding small decrease in the RF power delivered to the system (e.g., because the coupling is poorer at lower density). This can create cascading effect as the decreased RF power leads to further decreased plasma density, in turn leading to decreased RF power delivery until the plasma extinguishes. Because in many systems the plasma is lost on timescales of tens of microseconds, the resonant oscillators described herein may be incorporated into such systems to correct for the decreased coupled power on a shorter timescale than the plasma changes and advantageously prevent instability. Furthermore, since the instability can occur to some extent in all resonant systems (limiting the parameter range of operation), the

resonant oscillators described herein may combat this problem in any resonant system with the possible benefit of expanding the operational parameter range.

[0039] In the case of a plasma system where RF power used to generate plasma in a processing chamber, the plasma grows from near zero density to some initial low density within a few microseconds during striking and then continues to grow. The resonant frequency of the resonant load usually differs significantly between the empty chamber and the initial low-density plasma filled chamber (i.e., the plasma at the initial low density after striking). If the frequency of the RF power is preset to the empty chamber resonant frequency, the fields in the empty chamber are maximized and the initial breakdown (ionization of gases to generate plasma) occurs most easily. Therefore, deviation from the empty chamber resonant frequency decreases the fields in the empty chamber and plasma is generated less easily (i.e., less efficiently). If the frequency of the RF power is not set close enough to the empty chamber resonant frequency, then ignition of the plasma may not occur at all (or the power required to generate the plasma may be impractical). This may be particularly important at low chamber pressures where striking is more difficult to achieve.

[0040] Once a low-density plasma is achieved, the resonant frequency of the plasma system changes and the initial empty chamber resonant frequency is no longer optimal (because of the low-density plasma). As a result, the RF power delivered to the plasma at the empty chamber resonant frequency may be insufficient to allow it to grow (or at least the RF power may be inefficiently delivered requiring higher power to achieve the same effect while losing power to heat generated in components of the RF circuit). Since conventional plasma systems are not capable of adjusting the RF frequency quickly enough, a compromise RF frequency in between the optional striking frequency and the optimal plasma growth frequency may be chosen. The

difference between the compromise RF frequency and the empty chamber resonant frequency leads to a degradation in the ability to strike at low pressure.

[0041] Advantageously, the resonant oscillators described herein can adjust the RF frequency sufficiently quickly to maintain an optimum frequency throughout the entire striking transient. That is, the empty chamber resonant frequency may be used for striking and the frequency may be adjusted fast enough as the density of the plasma increases to match the resonant frequency of the load (now including the plasma) as the plasma density changes enabling striking at lower pressures and preventing premature extinguishing of the plasma after striking due to poorly coupled power.

[0042] Embodiments provided below describe various resonant oscillator circuits, and in particular, systems, apparatuses, and methods that include resonant oscillator circuits with a feedback circuit that includes a phase shifter. The following description describes the embodiments. FIG. 1 is used to describe an example resonant oscillator circuit. Four more example resonant oscillator circuits are described using FIGS. 2–5. Three example RF systems that include resonant oscillator circuits are described using FIGS. 6–8. An example plasma system that includes one or more resonant oscillator circuits is described using FIG. 9 while an example CCP plasma system and an example ICP plasma system are described using FIGS. 10 and 11 respectively. An example method of adjusting the frequency of RF power applied to a resonant load using a resonant oscillator circuit is described using FIG. 12.

[0043] FIG. 1 illustrates an example resonant oscillator circuit that includes a feedback circuit with a sensor coupled to RF power delivered at a power output of an amplifier and a phase shifter coupled between the sensor and a control input of the amplifier in accordance with embodiments of the invention. It should be noted that while here and in the following RF power

is used as a specific example, it is recognized that the principles involved apply equally well to AC signals of any frequency.

[0044] Referring to FIG. 1, a resonant oscillator circuit **101** includes a feedback circuit **120** and an amplifier **130**. The resonant oscillator circuit **101** is configured to deliver RF power **150** to a resonant load **110** from a power output **134** of the amplifier **130**. The feedback circuit **120** includes a sensor **124** that is coupled to the RF power **150** in such a way as to generate a feedback signal **152** that is a function of the waveform of the RF power **150** (i.e., the sensor **124** uses the RF power **150** to generate the feedback signal **152**). The feedback signal **152** is provided to feedback conditioning components **121** that alter one or more properties of the feedback signal **152** to generate a conditioned feedback signal **154**. The amplifier 130 has a control input **132** that is used to control the properties of the RF power **150** provided at the power output **134**.

[0045] The feedback conditioning components **121** may include various components, but at least includes a phase shifter **122** (i.e., a fixed phase shifter or a variable phase shifter) that is configured to modify the phase of the feedback signal **152**. The phase adjustment that generates the conditioned feedback signal **154** changes the resonant frequency of the resonant oscillator circuit **101**. For example, the resonant oscillator circuit **101** may operate as a feedback oscillator circuit that converges to a resonant frequency based on the structure and components of the resonant oscillator circuit **101** that determines the frequency of the RF power **150**. By adjusting the phase of the feedback signal **152**, the resonant frequency of the resonant oscillator circuit **101** can be changed thereby also changing the frequency of the RF power **150**. In this way, changes to the impedance of the resonant load **110** (e.g., the resonant frequency of the resonant load **110**)

can be counteracted by delivering the RF power **150** to the resonant load **110** at the new resonant frequency of the resonant load **110**.

[0046] The feedback signal **152** may be generally described as a superposition of sinusoidal waves (e.g., at discrete multiples of some fundamental frequency as a Fourier decomposition). That is, each Fourier component has an amplitude and a phase relative to the fundamental. The conditioned feedback signal **154** is generated by adjusting the amplitude and/or the phase of one or more of the Fourier components of the feedback signal **152**. This may be performed using various circuit components, including active circuit elements, such as one or more amplifiers, or passive circuit elements, such as transmission lines, passive filters, etc.

[0047] In some applications, additional elements may be included in the feedback circuit **120**. For example, an amplitude regulator may also be included in the feedback conditioning components **121** to adjust the amplitude of the feedback signal **152**. Another example of a possible additional element is a frequency shifter that is configured to manipulate the frequency of the feedback signal **152**. For example, it may be desirable to manipulate the frequency of the feedback signal **152** during various times, such as at the beginning of RF pulses (e.g., to get the pulse started as fast as possible). One possible implementation of a frequency shifter may be configured to inject a certain frequency into the feedback circuit. Another possible implementation may be to mix in another frequency into the feedback circuit. Software defined radio frequencies may also be used.

[0048] The feedback conditioning components **121** and in particular the phase shifter **122** may be configured to adjust the resonant frequency of the resonant oscillator circuit **101** at sufficiently short timescale to allow efficient coupling of the RF power **150** to a rapidly changing resonant load **110**. For example, the phase shifter **122** may be an analog phase shifter in an

embodiment. The analog phase shifter may be controlled by setting various operating parameters and the phase adjustment of the analog phase shifter may be on a shorter timescale than the timescale that the impedance of the resonant load **110** changes. In various embodiments, the feedback conditioning components **121** are configured to change the resonant frequency on a timescale at or shorter than about tens of microseconds. In some embodiments, the feedback conditioning components **121** are configured to change the resonant frequency on a timescale at or shorter than about 10 μs, and on a timescale at or shorter than about 2 μs in one embodiment.

[0049] The resonant oscillator circuit **101** may be considered a resonant phase-controlled oscillator because of the ability to alter the frequency of the RF power **150** using the feedback circuit **120** and the phase shifter **122**. The resonant oscillator circuit **101** may have a frequency bandwidth within which the frequency of the RF power **150** changes that may depend on the specific structure and components of the resonant oscillator circuit **101** (including the characteristics of the resonant load **110**, which may change). That is, the frequencies that may be delivered by the resonant oscillator circuit **101** are bounded by various properties of the circuit itself. The feedback circuit **120** with the phase shifter **122** is configured to generate the conditioned feedback signal **154** in order to expand the ability of the resonant oscillator circuit **101** to adjust the frequency of the RF power **150** in response to the changing impedance of the resonant load **110**. In various embodiments, the conditioned feedback signal **154** is configured to adjust the resonant frequency of the resonant oscillator circuit **101** within a frequency bandwidth less than about ten percent of the base resonant frequency (i.e., the base resonant frequency is the resonant frequency of the resonant oscillator circuit **101** if the phase shifter **122** does not alter the phase of the feedback signal **152**).

[0050] The resonant load **110** may be any resonant system. One example of a resonant system may be a resonant conductor, which resonates at a certain frequency due to its geometry (e.g., a resonant antenna, such as used to generate an ICP plasma). Another example of a resonant system is a non-resonant conductor (e.g., any conductor, one example of which would be an electrode, such as used to generate a CCP plasma, and that can also sometimes be referred to as an antenna) that is coupled to other lumped circuit elements (e.g., capacitors, inductors, etc.) so that the combination becomes a resonant system. In either case, the fields in the antenna structure may be maximized when the applied frequency is equal to the resonant frequency. In the case of a plasma system, the combined system of the resonant or non-resonant structure, the processing chamber, and the plasma may be the resonant load **110**.

[0051] However, as already mentioned, the resonant frequency of the resonant load **110** may depend on more than the resonant system itself. For example, in a plasma system, the resonant frequency may depend on the plasma properties, such as the plasma density (but also including other properties, such as the size and shape of the plasma). Thus, when RF power is applied to generate a plasma and the plasma density grows from approximately zero to some substantially constant value, the resonant frequency of the resonant load is changing. This is especially dramatic in pulsed systems, as the growth of the plasma density takes place on timescales of tens of microseconds while the RF pulses may be applied with comparative duration and at high pulse frequencies. This highlights the potential advantage of being able to adjust the drive frequency at similar or faster timescales (which is not possible with conventional systems).

[0052] While the capability of adjusting the phase of the feedback signal **152** dynamically over the course of a pulse may or may not be necessary, depending on the application, it may be a significant advantage in pulsed plasma systems where the plasma changes the impedance of the

resonant load **110** at timescales that are shorter than the pulse width. For this reason, the resonant oscillator circuit **101** would advantageously increase the coupling efficiency either way, but may have the benefit of achieving optimal coupling when the phase can be changed faster than a pulse.

[0053] The resonant load **110** may include various components that make up an RF circuit, such as a resonant structure. For example, in the specific case of a plasma system, the resonant structure may be a chamber antenna that is configured to couple RF power to a plasma. The chamber antenna may be the part of the RF circuit of the resonant load **110** that is adjacent to the plasma. The chamber antenna may include current carrying elements that are configured to produce time-varying magnetic fields and/or metal surfaces that are configured to accumulate charge due to RF fields and the accumulated charges may produce electric fields. Both the magnetic fields and the electric fields may then penetrate into the plasma, heating the plasma and affecting plasma properties, such as electrical potential. Coupled magnetic fields may be referred to as inductive coupling while coupled electric fields may be referred to as capacitive coupling, although both magnetic and electric fields are typically present in a given configuration.

[0054] The feedback circuit **120** is configured to generate feedback signal **152** using the sensor **124** by picking up the RF signal output by the amplifier **130** (the RF power **150** from the power output **134** that is also delivered to the resonant load **110**). The feedback signal **152** is then routed back to the control input **132** of the amplifier **130**. Specifically, the feedback signal **152** is modified by the phase shifter **122** (and other components in some embodiments) to generate the conditioned feedback signal **154** which is applied directly to the control input **132**. The control input **132** may be the gate of a transistor (e.g., the conditioned feedback signal **154**

may operate directly on the gate of the transistor). In other embodiments, other circuitry of the amplifier **130** (whether active or passive) may be included between the control input **132** and a transistor, such as logic circuitry, a microcontroller, etc.

[0055] In order for the resonant oscillator circuit **101** to operate as an oscillator, the phase of the conditioned feedback signal **154** may be constrained by the relationship between the control input **132** and the power output **134** of the amplifier **130**. That is, the amplifier **130** (e.g., including a transistor) has its own operating characteristics that may define acceptable parameter values at the control input **132** that will achieve the desired amplifier output. For example, with some transistor types, when the voltage at the control input **132** of the amplifier **130** is higher, the current at the power output **134** will also be higher. Correspondingly, when the voltage at the control input **132** of the amplifier **130** is low, the current at the power output **134** will also be lower and eventually be cut off entirely.

[0056] In the absence of the phase shifter **122**, the resonant oscillator circuit 101 has its own resonant frequency that is dependent on the various components in the feedback circuit **120**, but also dependent on the phase at the control input **132**. As a result, changing the phase of the feedback signal **152** using the phase shifter **122** also changes the resonant frequency of the resonant oscillator circuit **101**.

[0057] The feedback circuit **120** may include more than one sensor producing signals. These signals may be combined in the phase shifter **122** (or in a separate combiner unit) to produce a single signal with a phase that has been shifted relative to a reference phase. The reference phase may be the phase of the signal from the sensor **124**, or may be the phase of the signal from a predetermined one of the sensors if there are multiple. Other properties of the single or

combined feedback signal, such as amplitude, may also be adjusted before providing the conditioned feedback signal **154** at the control input **132** of the amplifier **130**.

[0058] The phase shifter **122** may be implemented in various ways. For example, the phase shifter **122** may be mechanical or electronic. A mechanical phase shifter may be configured to mechanically adjust the length of the transmission line through which the feedback signal **152** propagates to introduce a phase delay (e.g., because of the finite propagation speed of the feedback signal **152**). In contrast, an electronic phase shifter may be configured to use active electronic elements to modify the phase, such as by exploiting the fact that reactive elements like capacitors and inductors can change the phase of the feedback signal **152**.

[0059] The amplifier **130** is configured to output current (e.g., from a DC power source, such as a DC current source) with a waveform that is based on a signal received at the control input **132**. In various embodiments, the amplifier **130** includes one or more transistors with a power input node electrically coupled to a DC power source and a power output node (e.g., power output **134**) coupled to the resonant load **110**. The DC power source may include a current source that maintains a constant voltage (or constant current) and an RF choke configured to ensure that the current from the DC power source is not influenced by RF fluctuations. For example, the RF choke may be implemented using some combination of inductors and capacitors. A control node (e.g., a gate) of the one or more transistors may be coupled to the conditioned feedback signal **154** , which functions as a control signal.

[0060] The sensor **124** (e.g., a current sensor, voltage sensor, a directional coupler, etc.) is configured to generate a signal (i.e., the feedback signal **152**) that is dependent on a property of the output signal of the amplifier **130** (i.e., the RF power **150** being supplied to the resonant load **110**). For example, the sensor **124** may be a passive element, such as a pickup coil (for

generating a current proportional to the current of the output signal). In one implementation, the sensor **124** may be an antenna sensor (e.g., near or on an RF structure of the resonant load **110**, such as an antenna or an electrode, or on the processing chamber of a plasma system) that is configured to react to the output signal in the resonant load. Other sensors may also be included, such as sensors configured to measure reflected power, etc.

[0061] The sensor **124** may be any RF circuit element configured to couple to electromagnetic waves in a proximate RF circuit element, such as a transmission line, current carrying element, metallic structures immersed in a surrounding electromagnetic field environment, etc. The sensor **124** may be designed so that some of the electromagnetic wave energy is coupled to another lower level electromagnetic wave which then propagates as a signal to a device which senses its level. The sensor **124** may be purely passive, may contain active elements, such as transistors and amplifiers, or may be some combination thereof. In some embodiments, the sensor **124** is sensitive to the time-varying magnetic field produced by a time-varying current (i.e., a current "pickup" or current sensor). In other embodiments, the sensor **124** is sensitive to the time-varying electric field (i.e., a voltage "pickup" or voltage sensor). Of course, the sensor **124** may also be sensitive to some combination of time-varying electric and magnetic fields.

[0062] For example, the sensor may be configured so that electromagnetic waves moving in one direction on a transmission line are directed to one output port while waves moving in the opposite direction are directed to another output port; such a sensor may be called a "directional coupler". In general, sensors may be configured to be sensitive to electromagnetic waves and respond physically to the electromagnetic waves on a timescale that is less than the wave oscillation period. That is, it is desirable for a sensor to be able to detect information as to the

frequency, amplitude, and/or phase of the electromagnetic wave and relay that information electrically. For example, the sensor may relay this information in the form of a lower amplitude electromagnetic wave whose amplitude and phase are related to the amplitude and phase of the measured electromagnetic fields or it may relay the information as the amplitude and phase by other electrical means, whether analog or digital. This information, which may be modified by other circuitry, can then be used to regenerate the feedback signal **152** before it is applied as the conditioned feedback signal **154** to the control input **132** (e.g., a transistor control input port).

[0063] The amplifier **130** may have various components. For example, the amplifier **130** may include one or more active elements (e.g., power transistors, such as a field-effect transistor (FET), bipolar junction transistor (BJT), or other elements such as thyristors, etc.), a DC power source, a DC bias source, input and/or output impedance transformers, and others.

[0064] The sensor **124** may be placed in various locations in the resonant oscillator circuit **101** or in the resonant load **110**. In one embodiment, the sensor **124** is placed in the transmission (power) line carrying the RF power **150** between the amplifier **130** and the resonant load **110**. In this location, the sensor **124** may be configured to be sensitive to the fields in the transmission line which include the forward (transmitted) electromagnetic waves from the amplifier **130** and the reflected waves from resonant load **110**. The sensor **124** may also be placed inside or attached to an RF structure in the resonant load **110**. In this location, the sensor **124** may be configured to be directly sensitive to the electromagnetic fields of the resonant load. There may be advantages to having sensors in specific or multiple locations in the feedback circuit **120**. For example, having one or more sensors in the resonant load may be able to track signal properties over a larger frequency range. However, the desired capabilities of the sensors and sensor locations may depend on the needs of a given application.

[0065] FIG. 2 illustrates an example resonant oscillator circuit that includes a feedback circuit with both a phase shifter and an amplitude regulator in accordance with embodiments of the invention. The resonant oscillator circuit of FIG. 2 may be a specific implementation of other resonant oscillator circuits described herein such as the resonant oscillator circuit of FIG. 1, for example. Similarly labeled elements may be as previously described.

[0066] Referring to FIG. 2, a resonant oscillator circuit **201** includes a feedback circuit **220** and an amplifier **230**. It should be noted that here and in the following a convention has been adopted for brevity and clarity wherein elements adhering to the pattern [x01] where 'x' is the figure number may be related implementations of a resonant oscillator circuit in various embodiments. For example, the resonant oscillator circuit **201** may be similar to the resonant oscillator circuit **101** except as otherwise stated. An analogous convention has also been adopted for other elements as made clear by the use of similar terms in conjunction with the aforementioned numbering system.

[0067] The resonant oscillator circuit **201** is configured to deliver RF power **250** to a resonant load **210** from a power output **234** of the amplifier **230** using a sensor **224** coupled to the RF power **250** in such a way as to generate a feedback signal **252** according to the RF power **250**. Feedback conditioning components **221** include a phase shifter **222** and modify one or more properties of the feedback signal **252** to generate a conditioned feedback signal **254**, which is provided to a control input **232** of the amplifier **230**. The amplifier **230** is also shown with two example internal components: a DC power supply **236** configured to deliver DC power to an active element **238** (e.g., one or more transistors) at a power input **239**. The control input **232** may be control node of the active element **238** (e.g., a gate or gates of the transistor(s)) and may

control the flow of current from the DC power supply **236** through the active element **238** to the power output **234**.

[0068] In the specific example of the resonant oscillator circuit **201**, an amplitude regulator **226** is also be included in the feedback circuit **220**. The amplitude regulator **226** is configured to provide additional control over the behavior of the amplifier **230**. For example, the amplitude regulator **226** may be a preamplifier whose amplification is adjusted in order to produce a certain amplitude for the feedback signal **252** that will be applied to the control input **232** (e.g., a transistor gate). One purpose of controlling the input signal level may be to control the amplifier output power. Another purpose of controlling the input signal level may be to increase the efficiency of the amplifier (e.g., allowing transistor(s) to operate in class D mode, as opposed to class A mode). Still another purpose may be to protect the amplifier input from over-voltages.

[0069] In various embodiments, the amplitude may be adjusted using analog techniques, such as by using the RF amplitude of the amplifier output as an input or by comparison to a fixed signal level. The amplitude may also be adjusted using analog techniques in combination with control signals (e.g., from the controller) which may be analog or digital.

[0070] FIG. 3 illustrates an example resonant oscillator circuit that includes an amplifier with a DC power source coupled to a power input of a transistor through an RF choke as well as an optional DC bias and one or more optional impedance transformers in accordance with embodiments of the invention. The resonant oscillator circuit of FIG. 3 may be a specific implementation of other resonant oscillator circuits described herein such as the resonant oscillator circuit of FIG. 1, for example. Similarly labeled elements may be as previously described.

[0071] Referring to FIG. 3, a resonant oscillator circuit **301** includes a feedback circuit **320** and an amplifier **330**. The resonant oscillator circuit **301** is configured to deliver RF power **350** to a resonant load **310** from a power output **334** of the amplifier **330** using a sensor **324** coupled to the RF power **350** in such a way as to generate a feedback signal **352** according to the RF power **350**. Feedback conditioning components **321** (here including a phase shifter **322** and an amplitude regulator **326**, but may have different configurations) modify one or more properties of the feedback signal **352** to generate a conditioned feedback signal **354**, which is provided to a control input **332** of the amplifier **330**.

[0072] The amplifier **330** may have various components. For example, the amplifier **330** may include one or more active elements (e.g., power transistors, such as a FET, a BJT, or other elements such as thyristors, etc.). In this specific example, the amplifier **330** includes a transistor **338** with the control input **332** being the gate of the transistor **338**. Of course, the transistor **338** may be one of a pair of transistors (or many transistors). A DC power supply may be implemented as a DC power source **336** (such as a DC current source) coupled to a power input **339** of the transistor **338** through an RF choke **337**. A DC bias **335** may be coupled to the control input **332** and facilitate control over the voltage at the control input **332**. For example, the DC bias **335** may be configured to increase the voltage at the control input **332** to exceed a saturation threshold of the amplifier **330** (i.e., the transistor **338** and other transistors if an array of transistors is included) so that the amplifier **330** operates as a class D amplifier.

[0073] One or more impedance transformers (shown here as optional parts of the amplifier **330**) may also be included in the resonant oscillator circuit **301**. For example, an optional input impedance transformer **331** may be included between the feedback conditioning components **321** and the control input **332** to control the impedance of the control signal (i.e., the conditioned

feedback signal **354**). Similarly, an optional output impedance transformer **333** may be included after the power output **334** to control the impedance of the RF power **350**. Impedance transformers may be passive circuit elements that transform the impedance (e.g., collections of inductors, capacitors and or transformers). In various embodiments some or all of the impedance transformers included in the resonant oscillator circuit **301** may have flat frequency characteristics.

[0074] FIG. 4 illustrates an example resonant oscillator circuit that includes a feedback circuit with a sensor that is attached to a resonant load in accordance with embodiments of the invention. The resonant oscillator circuit of FIG. 4 may be a specific implementation of other resonant oscillator circuits described herein such as the resonant oscillator circuit of FIG. 1, for example. Similarly labeled elements may be as previously described.

[0075] Referring to FIG. 4, a resonant oscillator circuit **401** includes a feedback circuit **420** and an amplifier **430**. The resonant oscillator circuit **401** is configured to deliver RF power **450** to a resonant load **410** from a power output **434** of the amplifier **430** using a sensor **424** coupled to the RF power **450** in such a way as to generate a feedback signal **452** according to the RF power **450**. Feedback conditioning components **421** include a phase shifter **422** and modify one or more properties of the feedback signal **452** to generate a conditioned feedback signal **454**, which is provided to a control input **432** of the amplifier **430**.

[0076] In contrast to other resonant oscillator circuits discussed thus far, the sensor **424** is shown in this specific example to be attached to the resonant load **410** (e.g., attached to a structure (resonant or non-resonant) of the resonant load **410**, such as an RF antenna, source electrode, attached to a processing chamber such as a plasma chamber, etc.). Of course, other

positions may also be possible and other sensors may also be included, as illustrated in the following figure.

[0077] FIG. 5 illustrates an example resonant oscillator circuit that includes a feedback circuit with a first sensor that is coupled in series with a transmission line between the power output of an amplifier and a resonant load as well as a second sensor that is attached to the resonant load in accordance with embodiments of the invention. The resonant oscillator circuit of FIG. 5 may be a specific implementation of other resonant oscillator circuits described herein such as the resonant oscillator circuit of FIG. 1, for example. Similarly labeled elements may be as previously described.

[0078] Referring to FIG. 5, a resonant oscillator circuit **501** includes a feedback circuit **520** and an amplifier **530**. The resonant oscillator circuit **501** is configured to deliver RF power through a transmission line **550** to a resonant load **510** from a power output **534** of the amplifier **530** using a first sensor **524** coupled to the RF power (e.g., in series with the transmission line **550**) in such a way as to generate a first feedback signal **552** according to the RF power. Feedback conditioning components **521** include a phase shifter **522** and modify one or more properties of the first feedback signal **552** to generate a conditioned feedback signal **554**, which is provided to a control input **532** of the amplifier **530**.

[0079] In the specific example of the resonant oscillator circuit **501**, a second sensor **525** is also included, shown as attached to the resonant load **510** (similar to the sensor **424**). The second sensor **525** may be configured to generate its own second feedback signal **553** that may be provided to the feedback conditioning components **521** separately from the first feedback signal **552** (as shown) or may be combined before the feedback conditioning components **521**. Internally, the first feedback signal **552** and the second feedback signal **553** may be separately

modified or a combined signal may be modified by and of the feedback conditioning components **521**. Clearly, although two sensors are shown in this specific example, more sensors may be included, whether in different locations in the resonant oscillator circuit **501** or in similar locations, but different positions (e.g., different part of the transmission line **550**, different region of the resonant load **510**, etc.).

[0080] FIG. 6 illustrates an example RF system that includes a resonant oscillator circuit and a controller configured to send a phase control signal to a phase shifter of a feedback circuit of the resonant oscillator circuit and to receive a sensor signal from a sensor of the feedback circuit in accordance with embodiments of the invention. The RF system of FIG. 6 may include any of the resonant oscillator circuits described herein, such as the resonant oscillator circuit of FIG. 1, for example. Similarly labeled elements may be as previously described.

[0081] Referring to FIG. 6, an RF system **600** includes a resonant oscillator circuit **601** that includes a feedback circuit **620** and an amplifier **630**. The resonant oscillator circuit **601** is configured to deliver RF power **650** to a resonant load **610** from a power output **634** of the amplifier **630** using a sensor **624** coupled to the RF power **650** in such a way as to generate a feedback signal **652** according to the RF power **650**. Feedback conditioning components **621**, including a phase shifter **622**, modify one or more properties of the feedback signal **652** to generate a conditioned feedback signal **654**, which is provided to a control input **632** of the amplifier **630**.

[0082] In addition to the resonant oscillator circuit **601**, the RF system **600** also includes a controller **640**. The controller **640** is configured to control various elements in the resonant oscillator circuit **601**. For example, the controller **640** is configured to control the phase shifter **622** using a phase control signal **655**. That is, the phase of the conditioned feedback signal **654**

is controlled by the phase shifter **622**, which in turn is controlled by the controller **640** (e.g., directly or through setting operating parameters). Of course, when other elements are present in the resonant oscillator circuit **601** (such as in the feedback conditioning components **621** or the amplifier **630**), the controller **640** may be configured to control some or all of the additional controllable elements.

[0083] The controller **640** may be configured to receive a sensor signal **656** from the sensor **624**. For example, the sensor signal **656** may provide information to the controller **640** about the properties of the RF power **650**. This information may then be used by the controller **640** to appropriately control the phase shifter **622** using the phase control signal **655** (as well as other elements when present). In various embodiments, the controller **640** controls the phase adjustment of the phase shifter **622** according to the sensor signal **656**. The controller **640** may have inputs from multiple sensors as well as from outside the RF system **600** (e.g., to allow the configuration of the RF system **600** to be determined using set points).

[0084] In addition to the sensors already discussed, the sensor inputs to the controller **640** may include sensors that reflect parameters of the RF system **600** such as its oscillation frequency, thermal data, electromagnetic field strengths, forward and backward wave strengths, as well as further sensors, such as pressure sensors, photodiodes, plasma optical emission spectrometers, and microwave interferometers, and also external tool settings (e.g., from a recipe for a process), such as gas valve settings, settings related to pulse parameters, total recipe time duration, etc.

[0085] The controller **640** may include digital elements and analog elements. For example, the controller **640** may control the controllable elements of the resonant oscillator circuit **601** using an analog circuit, through a digital circuit (which may reference stored data and numerical

algorithms), or a combination of the two. Such data and numerical algorithms may be changed externally and/or may modify themselves on the basis of data acquired by the controller **640** based on its sensors. In some cases, using analog elements may enhance the speed of the controller **640** (which, as already discussed, may be important for maintaining optimal power delivery in rapidly changing resonant systems). The analog elements may then themselves be controlled using digital elements, such as by using digital elements to set operating parameters of the analog elements. The phase shifter **622** may combine signals from different sensors (sensor **624** and others) to produce a single signal with a particular phase shift, and the function for combining the several signals may also be controllable by the controller **640**.

[0086] FIG. 7 illustrates an example RF system that includes a resonant oscillator circuit and a controller configured to send an amplitude control signal to an amplitude regulator of a feedback circuit of the resonant oscillator circuit and to receive a sensor signal from a sensor of the feedback circuit in accordance with embodiments of the invention. The RF system of FIG. 7 may be a specific implementation of other RF systems described herein such as the RF system of FIG. 6, for example. Similarly labeled elements may be as previously described.

[0087] Referring to FIG. 7, an RF system **700** includes a resonant oscillator circuit **701** that includes a feedback circuit **720** and an amplifier **730**. The resonant oscillator circuit **701** is configured to deliver RF power **750** to a resonant load **710** from a power output **734** of the amplifier **730** using a sensor **724** coupled to the RF power **750** in such a way as to generate a feedback signal **752** according to the RF power **750**. Feedback conditioning components **721**, which include a phase shifter **722** and an amplitude regulator **726**, modify one or more properties of the feedback signal **752** to generate a conditioned feedback signal **754**, which is provided to a

control input **732** of the amplifier **730**. The amplifier **730** includes a DC power supply **736** that is configured to deliver DC power at a power input **739** of an active element **738**.

[0088] Similar to the preceding RF system, the RF system **700** also includes a controller **740** that is configured to receive a sensor signal **756** from the sensor **724** and control the phase shifter **722** using a phase control signal **755**. Additionally, since the amplitude regulator **726** is also included in the feedback conditioning components **721**, the controller **740** is further configured to control the amplitude regulator **726** using an amplitude control signal **759**.

[0089] FIG. 8 illustrates an example RF system that includes a resonant oscillator circuit and a controller configured to send various control signals to components of an amplifier of the resonant oscillator circuit and to receive a sensor signal from a sensor of a feedback circuit of the resonant oscillator circuit in accordance with embodiments of the invention. The RF system of FIG. 8 may be a specific implementation of other RF systems described herein such as the RF system of FIG. 6, for example. Similarly labeled elements may be as previously described.

[0090] Referring to FIG. 8, an RF system **800** includes a resonant oscillator circuit **801** that includes a feedback circuit **820** and an amplifier **830**. The resonant oscillator circuit **801** is configured to deliver RF power to a resonant load **810** from a power output **834** of the amplifier **830** using a first sensor **824** and a second sensor **825**. The first sensor **824** is coupled to the RF power (transmission line **850**) in such a way as to generate a first feedback signal **852**. The second sensor **825** is coupled to the resonant load **810** (e.g., attached to a structure) so that a second feedback signal **853** is generated.

[0091] Feedback conditioning components **821**, which include a phase shifter **822** and a amplitude regulator **826**, modify one or more properties of the first feedback signal **852** and the

second feedback signal **853** (e.g., a signal combined in the phase shifter **822**) to generate a conditioned feedback signal **854**, which is provided to a control input **832** of the amplifier **830**. The amplifier **830** includes a transistor **838** with the control input **832** being the gate of the transistor **838**. A DC power supply may be implemented as a DC power source **836** (such as a DC current source) coupled to a power input **839** of the transistor **838** through an RF choke **837**. An optional DC bias **835** may be coupled to the control input **832** and facilitate control over the voltage at the control input **832**.

[0092] The RF system **800** further includes a controller **840** that is configured to receive a sensor signal **856** from the first sensor **824** and a second sensor signal **857** from the second sensor **825** (and may receive addition sensor signals as well as external inputs **851**, which may include various feedforward control information, such as process recipes, sequencing information, etc.) and control the phase shifter **822** using a phase control signal **855**. The controller **840** may also be configured to control some or all of the other controllable elements included in the resonant oscillator circuit **801**. For example, the amplitude regulator **826** may also be controlled by the controller **840** using an amplitude control signal **859**. Additional RF measurements between signal points may also be included, such as phase measurements, gain measurements, and/or frequency measurements. For example, these signals can be used for controlling components such as the amplitude regulator 826, the phase shifter 822, the transistor 838, the first sensor 824, the second sensor 825, and so on.

[0093] Various additional controllable elements are shown as part of the amplifier **830** (some being optional). For example, the controller **840** may be configured to control an optional feedback impedance transformer **831** and an optional power impedance transformer **833** using a feedback impedance control signal **861** and a power impedance control signal **863**, respectively.

The optional feedback impedance transformer **831** and the optional power impedance transformer **833** are configured to adjust the impedance of the resonant oscillator circuit **801**. In some cases, other changes to the RF waves passing through the transformers may occurs, such as changes to phase, which may contribute the overall character of the conditioned feedback signal **854**. The impedance of the resonant oscillator circuit **801** may be adjusted by the optional feedback impedance transformer **831** and/or the optional power impedance transformer **833** for various reasons, including adjusting the input/output impedance experienced by the transistor **838** to desirable (e.g., optimal) values as the frequency changes, adjusting the phase contribution of the transformers themselves, and others. A bias control signal **865** may be used by the controller **840** to control the optional DC bias **835**. Similarly, the controller **840** may be configured to control the DC power source **836** using a DC power control signal **866**.

[0094] The controller **840** may include an optional processor **842** and/or an optional memory **844** (i.e., a non-transitory computer-readable medium) that stores a program including instructions that, when executed by the optional processor **842**, control the phase shifter **822** and other controllable elements of the resonant oscillator circuit **801**. For example, the optional memory **844** may have volatile memory (e.g., random access memory (RAM)) and non-volatile memory (e.g., flash memory). Alternatively, the program may be stored in physical memory at a remote location, such as in cloud storage. The optional processor **842** may be any suitable processor, such as the processor of a microcontroller, a general-purpose processor (such as a central processing unit (CPU), a microprocessor, a field-programmable gate array (FPGA), an application-specific integrated circuit (ASIC), and others.

[0095] FIG. 9 illustrates an example plasma system that includes a feedback circuit coupled to RF power delivered to a resonant load that includes a plasma chamber, an RF structure

configured to generate a plasma in the plasma chamber using the RF power, and the plasma where the feedback circuit includes a phase shifter in accordance with embodiments of the invention. The plasma system of FIG. 9 may be a specific implementation of RF systems described herein such as the RF system of FIG. 6, for example. Similarly labeled elements may be as previously described.

[0096] Referring to FIG. 9, a plasma system **900** (such as a pulsed plasma system) includes a RF structure **912** that is configured to generate a plasma **916** in a plasma chamber **914** (e.g., to process a substrate **919** supported by a substrate support **918**, such as a plasma etching chamber, a plasma deposition chamber, etc.) using RF power delivered to the RF structure **912** by an RF source power supply **902** through a source transmission line **950**. The RF structure **912** may be any suitable structure, including antenna structures, electrode structures, waveguides, etc. The plasma system **900** is a pulsed plasma system in various embodiments, configured to deliver RF power to the RF structure **912** as a series of RF pulses at a desired pulse frequency, pulse width, and duty cycle.

[0097] The RF source power supply **902** includes a resonant oscillator circuit **901** that includes a feedback circuit **920** and an amplifier **930**. The resonant oscillator circuit **901** is configured to deliver the RF power to a resonant load **910** (here including the RF structure **912**, the plasma chamber **914**, and the plasma **916**, once it is generated). The RF power is delivered through the source transmission line **950** from a power output **934** of the amplifier **930** using a sensor **924** coupled to the RF power so that a feedback signal **952** is generated according to the RF power. Feedback conditioning components **921**, including at least a phase shifter **922**, modify one or more properties of the feedback signal **952** to generate a conditioned feedback signal **954**, which is provided to a control input **932** of the amplifier **930**.

[0098] A controller **940** (which may include an optional processor **942** and/or an optional memory **944**) is configured to control the resonant oscillator circuit **901**. For example, the controller **940** may control the phase shifter **922** using a phase control signal **955**. The sensor **924** may send a sensor signal **956** indicating an attribute or state of the source transmission line **950** to the controller **940**.

[0099] In some implementations, RF power may also be delivered to the substrate support **918** (often referred to as bias power) from an optional RF bias power supply **904** through a bias transmission line **960**. The optional RF bias power supply **904** may also include an optional bias resonant oscillator circuit **903** that may be configured to adjust the phase of a feedback signal to efficiently couple the RF power to the substrate support **918**. Specifically, the optional bias resonant oscillator circuit **903** may be similar to the resonant oscillator circuit **901** (also including a feedback circuit with a phase shifter and an amplifier). When included, the optional bias resonant oscillator circuit **903** may be controlled by the controller **940** using a bias phase control signal **967** (e.g., based on information received from at least one bias sensor signal **968**).

[0100] FIG. 10 illustrates an example plasma system where the RF structure is implemented as an upper electrode of a capacitively coupled plasma (CCP) plasma system in accordance with embodiments of the invention. The CCP plasma system of FIG. 10 may be a specific implementation of other plasma systems described herein such as the plasma system of FIG. 9, for example. Similarly labeled elements may be as previously described.

[0101] Referring to FIG. 10, a CCP plasma system **1000** includes a UEL **1012** (an upper electrode, which may be a non-resonant structure) that is configured to generate a plasma **1016** in a plasma chamber **1014** (e.g., to process a substrate **1019** supported by a LEL **1018** (lower electrode that here is also a substrate support) using RF power delivered to the UEL **1012** by an

RF source power supply **1002** through a source transmission line **1050**, which may also include a power return structure, such as the outer conductor of a coaxial feed. The plasma chamber **1014** may be coupled to a ground potential **1046**, which may be implemented as a reference potential that is configured to function as a substantially infinite charge sink in the context of the CCP plasma system **1000**, or be earth ground, whether directly or indirectly). Further, the ground potential **1046** may be configured as a common return. The CCP plasma system **1000** is a pulsed plasma system in various embodiments.

[0102] The RF source power supply **1002** includes a resonant oscillator circuit **1001** configured to deliver the RF power to a resonant load **1010** (including the UEL **1012**, the plasma chamber **1014**, and the plasma **1016**, once it is generated). An optional RF bias power supply **1004** may deliver RF power to the LEL **1018** through a bias transmission line **1060**. The optional RF bias power supply **1004** may also include an optional bias resonant oscillator circuit **1003**.

[0103] A controller **1040** (which may include an optional processor **1042** and/or an optional memory **1044**) is configured to receive a source sensor signal **1056** from the resonant oscillator circuit **1001** and control the resonant oscillator circuit **1001** using a source phase control signal **1055**. Similarly, the optional bias resonant oscillator circuit **1003** (when included) may be configured to receive a bias sensor signal **1068** and control the optional bias resonant oscillator circuit **1003** using a bias phase control signal **1067**.

[0104] FIG. 11 illustrates an example plasma system where the RF structure is implemented as an RF antenna of an inductively coupled plasma (ICP) plasma system in accordance with embodiments of the invention. The ICP plasma system of FIG. 11 may be a specific

implementation of other plasma systems described herein such as the plasma system of FIG. 9, for example. Similarly labeled elements may be as previously described.

[0105] Referring to FIG. 11, an ICP plasma system **1100** includes an RF antenna **1112** (e.g., a chamber antenna placed on or adjacent to a plasma chamber **1114** separated by a dielectric material **1148** allowing electromagnetic fields to penetrate into the plasma chamber **1114** from the RF antenna **1112**) that is configured to generate a plasma **1116** in the plasma chamber **1114** (e.g., to process a substrate **1119** supported by a substrate support **1118** (lower electrode that here is also a substrate support) using RF power delivered to the RF antenna **1112** by an RF source power supply **1102** through a source transmission line **1150**. For example, the RF antenna **1112** may be resonant structure like a resonant coil, such as a planar spiral coil, as shown (of course it could also be a helical coil or any one of many other types of resonant RF antenna structures). The plasma chamber **1114** may be coupled to a ground potential **1146**. The ICP plasma system **1100** is a pulsed plasma system in various embodiments.

[0106] The RF source power supply **1102** includes a resonant oscillator circuit **1101** configured to deliver the RF power to a resonant load **1110** (including the RF antenna **1112**, the plasma chamber **1114**, and the plasma **1116**, once it is generated). An optional RF bias power supply **1104** may deliver RF power to the substrate support **1118** through a bias transmission line **1160**. The optional RF bias power supply **1104** may also include an optional bias resonant oscillator circuit **1103**.

[0107] A controller **1140** (which may include an optional processor **1142** and/or an optional memory **1144**) is configured to receive a source sensor signal **1156** from the resonant oscillator circuit **1101** and control the resonant oscillator circuit **1101** using a source phase control signal **1155**. Similarly, the optional bias resonant oscillator circuit **1103** (when included) may be

configured to receive a bias sensor signal **1168** and control the optional bias resonant oscillator circuit **1103** using a bias phase control signal **1167**.

[0108] FIG. 12 illustrates an example method of adjusting the frequency of RF power applied to a resonant load in accordance with embodiments of the invention. The method of FIG. 12 may be combined with other methods and performed using the systems and apparatuses as described herein. For example, the method of FIG. 12 may be combined with any of the embodiments of FIGS. 1–11. Although shown in a logical order, the arrangement and numbering of the steps of FIG. 12 are not intended to be limited. The method steps of FIG. 12 may be performed in any suitable order or concurrently with one another as may be apparent to a person of skill in the art.

[0109] Referring to FIG. 12, a method **1200** of adjusting the frequency of RF power applied to a resonant load includes a step **1201** of generating RF power at a first frequency by supplying current to an amplifier of a resonant oscillator circuit. It should be understood that while the RF power is delivered at a first frequency, this is not necessarily a specific frequency value imposed on the resonant oscillator, but may instead be a function of the configuration of the circuit as a resonant circuit coupled to the resonant load. When current is supplied to the amplifier, the resonant oscillator circuit generates the RF power at a frequency (i.e., the first frequency). The RF power is delivered from a power output of the amplifier to a resonant load in step **1202** (e.g., substantially simultaneously with generation of the RF power in step **1201**, but of course some small delay based on transmission implementation may be present). The resonant load has a resonant frequency.

[0110] In step **1203**, a feedback signal is generated using the RF power. The feedback signal indicates a change in the resonant frequency to a second resonant frequency. Step **1204** includes

adjusting the phase of the feedback signal to generate a conditioned feedback signal, which is applied to the control input to generate RF power at the second resonant frequency in step **1205**. In this context "at" the second resonant frequency includes substantially similar frequencies, although the RF power generated in step **1205** may match the second resonant frequency exactly or nearly exactly in many cases.

[0111] Example embodiments of the invention are summarized here. Other embodiments can also be understood from the entirety of the specification as well as the claims filed herein.

[0112] Example 1. A resonant oscillator circuit including: an amplifier including a control input and a power output configured to deliver RF power to a resonant load; and a feedback circuit including a sensor coupled to the RF power and configured to generate a feedback signal using the RF power, and a phase shifter coupled between the control input and the sensor, the phase shifter being configured to adjust a phase of the feedback signal to provide a conditioned feedback signal at the control input.

[0113] Example 2. The resonant oscillator circuit of example 1, where the phase shifter is a fixed phase shifter.

[0114] Example 3. The resonant oscillator circuit of example 1, where the phase shifter is a variable phase shifter.

[0115] Example 4. The resonant oscillator circuit of one of examples 1 to 3, where the sensor is a current sensor, a voltage sensor, or a directional coupler.

[0116] Example 5. The resonant oscillator circuit of one of examples 1 to 4, where the feedback circuit further includes an amplitude regulator configured to adjust amplitude of the feedback signal to provide the conditioned feedback signal at the control input.

[0117] Example 6. The resonant oscillator circuit of one of examples 1 to 5, further including a controller operatively coupled to the sensor and the phase shifter, the controller being configured to control adjusting the phase of the feedback signal according to a sensor signal received from the sensor.

[0118] Example 7. The resonant oscillator circuit of example 4, where the resonant oscillator circuit is part of a pulsed plasma system configured to generate a plasma in a plasma chamber by pulsing the RF power to an RF structure, and where the resonant load includes the plasma, the plasma chamber, and the RF structure.

[0119] Example 8. The resonant oscillator circuit of one of examples 1 to 7, further including a DC bias coupled to the control input and configured to increase voltage at the control input to exceed a saturation threshold of the amplifier so that the amplifier operates as a class D amplifier.

[0120] Example 9. The resonant oscillator circuit of one of examples 1 to 8, further including an impedance transformer with flat frequency characteristics.

[0121] Example 10. An RF system including: a resonant oscillator circuit including an amplifier including a control input and a power output configured to deliver RF power to a resonant load, and a feedback circuit including a sensor coupled to the RF power and configured to generate a feedback signal using the RF power, and a phase shifter coupled between the control input and the sensor; and a controller operatively coupled to the sensor and the phase shifter, the controller being configured to control the phase shifter to adjust a phase of the feedback signal according to a sensor signal received from the sensor to provide a conditioned feedback signal at the control input.

[0122] Example 11. The RF system of example 10, where the phase of the feedback signal is adjusted at a timescale of tens of microseconds or less.

[0123] Example 12. The RF system of one of examples 10 and 11, where the phase shifter is an analog phase shifter, and where the controller is configured to set operating parameters of the analog phase shifter using digital elements.

[0124] Example 13. The RF system of one of examples 10 to 12, where the feedback circuit further includes an amplitude regulator operatively coupled to the controller, and where the controller is further configured to control the amplitude regulator to adjust amplitude of the feedback signal according to the sensor signal to provide the conditioned feedback signal at the control input.

[0125] Example 14. The RF system of one of examples 10 to 13, further including an impedance transformer operatively coupled to the controller, where the controller is further configured to control the impedance transformer to adjust impedance of the resonant oscillator circuit according to the sensor signal.

[0126] Example 15. The RF system of one of examples 10 to 14, where the amplifier further includes: a transistor including the control input, the power output, and a power input; and a DC power supply electrically coupled to the power input through an RF choke, the controller being further configured to control the DC power supply to provide DC power at the power input.

[0127] Example 16. A plasma system including: a plasma chamber; an RF structure configured to generate a plasma in the plasma chamber using RF power; a resonant load including the RF structure, the plasma chamber, and the plasma; a transistor including a control input, a power input, and a power output configured to deliver the RF power to the resonant load;

a DC power supply coupled to the power input of the transistor; and a feedback circuit including a sensor coupled to the RF power and configured to generate a feedback signal using the RF power, and a phase shifter coupled between the control input and the sensor, the phase shifter being configured to adjust a phase of the feedback signal to provide a conditioned feedback signal at the control input.

[0128] Example 17. The plasma system of example 16, further including: a controller operatively coupled to the DC power supply, the sensor, and the phase shifter, the controller being configured to control the phase shifter to adjust the phase of the feedback signal according to a sensor signal received from the sensor, and control the DC power supply to provide DC power at the power input of the transistor.

[0129] Example 18. The plasma system of one of examples 16 and 17, where the sensor is coupled in series with a transmission line between the power output of the transistor and the resonant load.

[0130] Example 19. The plasma system of one of examples 16 and 17, where the sensor is attached to the plasma chamber.

[0131] Example 20. The plasma system of one of examples 16 to 19, where the plasma system is a pulsed plasma system configured to generate the plasma in the plasma chamber by pulsing the RF power to the RF structure.

[0132] While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications and combinations of the illustrative embodiments, as well as other embodiments of the invention,

will be apparent to persons skilled in the art upon reference to the description. It is therefore intended that the appended claims encompass any such modifications or embodiments.

WHAT IS CLAIMED IS:

1. A resonant oscillator circuit comprising:

an amplifier comprising a control input and a power output configured to deliver RF power to a resonant load; and

a feedback circuit comprising

a sensor coupled to the RF power and configured to generate a feedback signal using the RF power, and

a phase shifter coupled between the control input and the sensor, the phase shifter being configured to adjust a phase of the feedback signal to provide a conditioned feedback signal at the control input.

2. The resonant oscillator circuit of claim 1, wherein the phase shifter is a fixed phase shifter.

3. The resonant oscillator circuit of claim 1, wherein the phase shifter is a variable phase shifter.

4. The resonant oscillator circuit of claim 1, wherein the sensor is a current sensor, a voltage sensor, or a directional coupler.

5. The resonant oscillator circuit of claim 1, wherein the feedback circuit further comprises an amplitude regulator configured to adjust amplitude of the feedback signal to provide the conditioned feedback signal at the control input.

6. The resonant oscillator circuit of claim 1, further comprising a controller operatively coupled to the sensor and the phase shifter, the controller being configured to control adjusting the phase of the feedback signal according to a sensor signal received from the sensor.

7. The resonant oscillator circuit of claim 4, wherein the resonant oscillator circuit is part of a pulsed plasma system configured to generate a plasma in a plasma chamber by pulsing the RF power to an RF structure, and wherein the resonant load comprises the plasma, the plasma chamber, and the RF structure.

8. The resonant oscillator circuit of claim 1, further comprising a direct current (DC) bias coupled to the control input and configured to increase voltage at the control input to exceed a saturation threshold of the amplifier so that the amplifier operates as a class D amplifier.

9. The resonant oscillator circuit of claim 1, further comprising an impedance transformer with flat frequency characteristics.

10. A radio frequency (RF) system comprising:

a resonant oscillator circuit comprising

an amplifier comprising a control input and a power output configured to deliver RF power to a resonant load, and

a feedback circuit comprising

a sensor coupled to the RF power and configured to generate a feedback signal using the RF power, and

a phase shifter coupled between the control input and the sensor; and

a controller operatively coupled to the sensor and the phase shifter, the controller being configured to control the phase shifter to adjust a phase of the feedback signal according to a sensor signal received from the sensor to provide a conditioned feedback signal at the control input.

11. The RF system of claim 10, wherein the phase of the feedback signal is adjusted at a timescale of tens of microseconds or less.

12. The RF system of claim 10, wherein the phase shifter is an analog phase shifter, and wherein the controller is configured to set operating parameters of the analog phase shifter using digital elements.

13. The RF system of claim 10, wherein the feedback circuit further comprises an amplitude regulator operatively coupled to the controller, and wherein the controller is further configured to control the amplitude regulator to adjust amplitude of the feedback signal according to the sensor signal to provide the conditioned feedback signal at the control input.

14. The RF system of claim 10, further comprising an impedance transformer operatively coupled to the controller, wherein the controller is further configured to control the impedance transformer to adjust impedance of the resonant oscillator circuit according to the sensor signal.

15. The RF system of claim 10, wherein the amplifier further comprises:

a transistor comprising the control input, the power output, and a power input; and

a direct current (DC) power supply electrically coupled to the power input through an RF choke, the controller being further configured to control the DC power supply to provide DC power at the power input.

16. A plasma system comprising:

a plasma chamber;

a radio frequency (RF) structure configured to generate a plasma in the plasma chamber using RF power;

a resonant load comprising the RF structure, the plasma chamber, and the plasma;

a transistor comprising a control input, a power input, and a power output configured to deliver the RF power to the resonant load;

a direct current (DC) power supply coupled to the power input of the transistor; and

a feedback circuit comprising

a sensor coupled to the RF power and configured to generate a feedback signal using the RF power, and

a phase shifter coupled between the control input and the sensor, the phase shifter being configured to adjust a phase of the feedback signal to provide a conditioned feedback signal at the control input.

17. The plasma system of claim 16, further comprising:

a controller operatively coupled to the DC power supply, the sensor, and the phase shifter, the controller being configured to

control the phase shifter to adjust the phase of the feedback signal according to a sensor signal received from the sensor, and

control the DC power supply to provide DC power at the power input of the transistor.

18. The plasma system of claim 16, wherein the sensor is coupled in series with a transmission line between the power output of the transistor and the resonant load.

19. The plasma system of claim 16, wherein the sensor is attached to the plasma chamber.

20. The plasma system of claim 16, wherein the plasma system is a pulsed plasma system configured to generate the plasma in the plasma chamber by pulsing the RF power to the RF structure.