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Ahmadi

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(54) **CLASS-E POWER OSCILLATOR**

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H03B 5/24 (2006.01)
H03F 3/217 (2006.01)
H03F 1/02 (2006.01)

(52) **U.S. Cl.**
CPC **H03F 1/0205** (2013.01); **H03B 1/02** (2013.01); **H03B 5/24** (2013.01); **H03F 3/2176** (2013.01); **H03F 2200/129** (2013.01)

(58) **Field of Classification Search**

CPC H03B 1/02; H03B 5/20; H03B 5/24; H03F 1/0205; H03F 3/2176; H03F 2200/129
See application file for complete search history.

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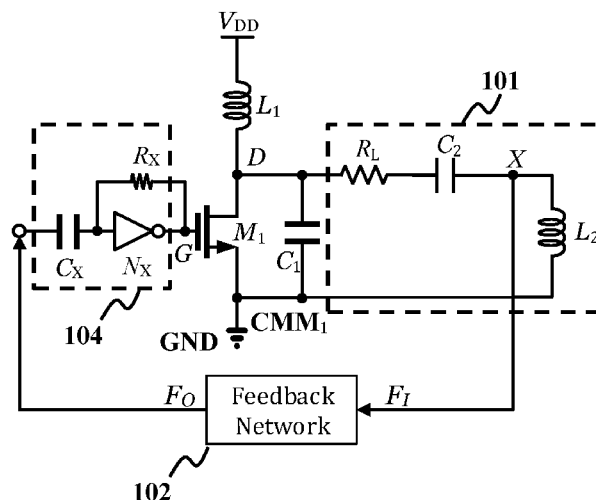
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(57) **ABSTRACT**

A class-E power oscillator (PO) is disclosed. The class-E PO includes a first inductor, a switch, a first capacitor, a resonant circuit, and a feedback network. The first inductor is coupled in series to a first power supply. The switch is connected between the first inductor and a primary common node. The first capacitor is connected between the first inductor and the primary common node. The resonant circuit includes a second inductor, a second capacitor, and a resistor. The second inductor is connected between the first inductor and the primary common node. The second capacitor is connected between the first inductor and the primary common node, and is coupled in series to the second inductor. The resistor is connected between the first inductor and the primary common node, and is coupled in series to the second inductor. The feedback network is connected between the switch and a feedback node. The feedback node is located between the second inductor and the second capacitor. The feedback network is configured to periodically turn the switch on and off based on a resonance frequency of the resonant circuit.

19 Claims, 17 Drawing Sheets

100G



100A

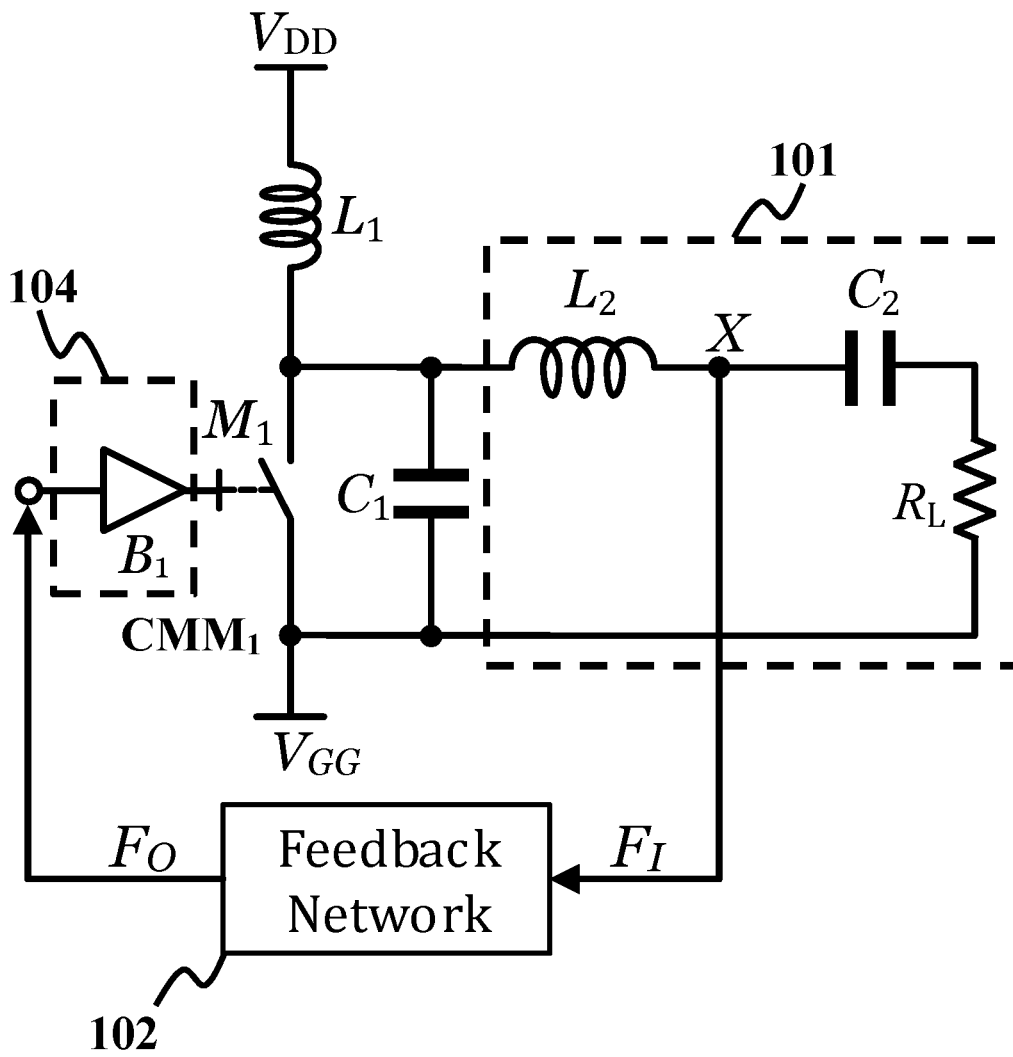


FIG. 1A

100B

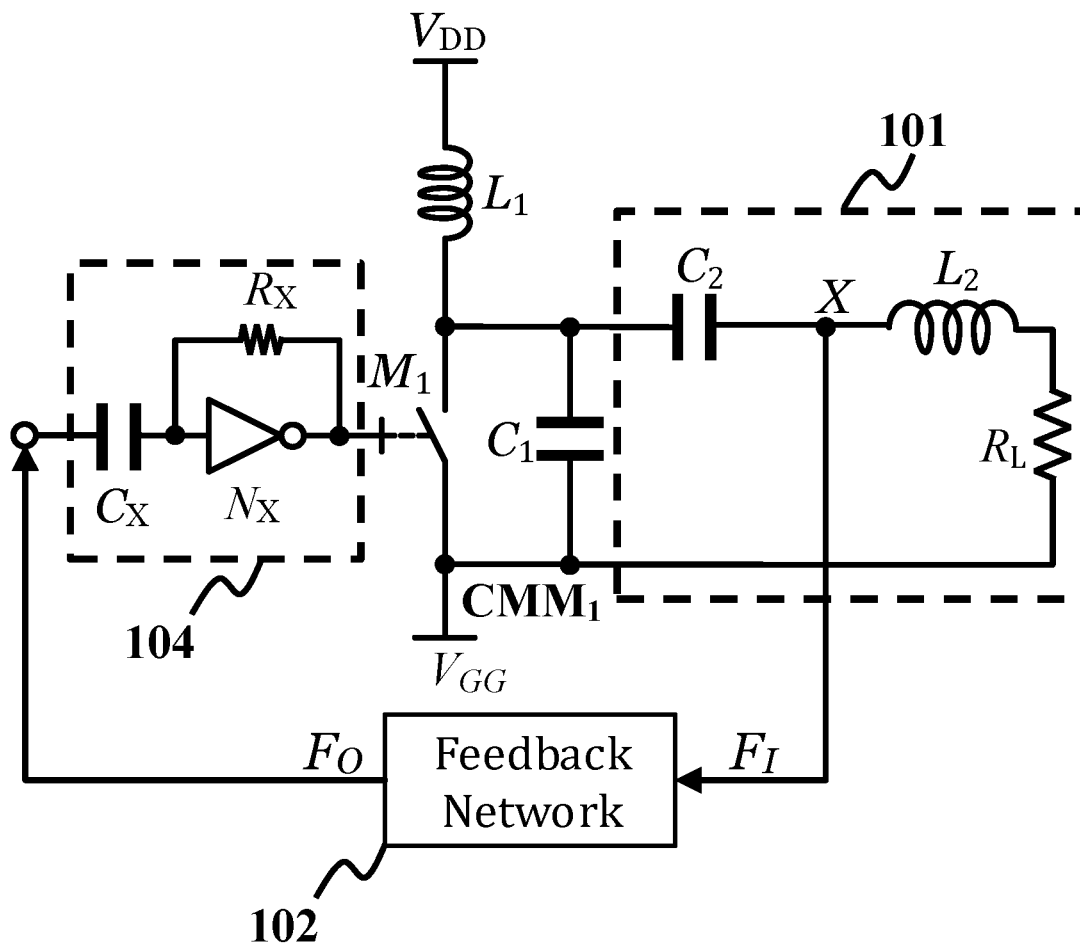


FIG. 1B

100C

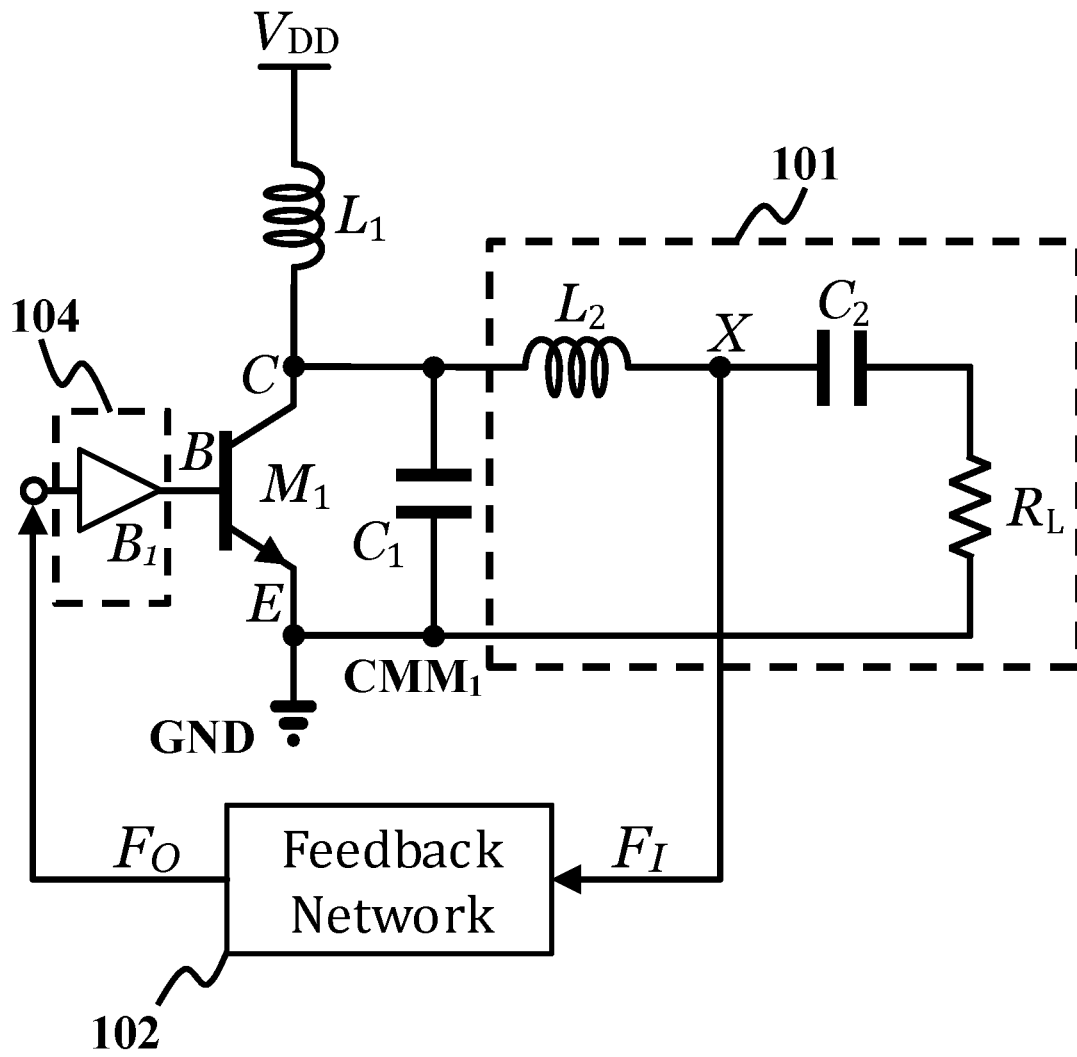


FIG. 1C

100D

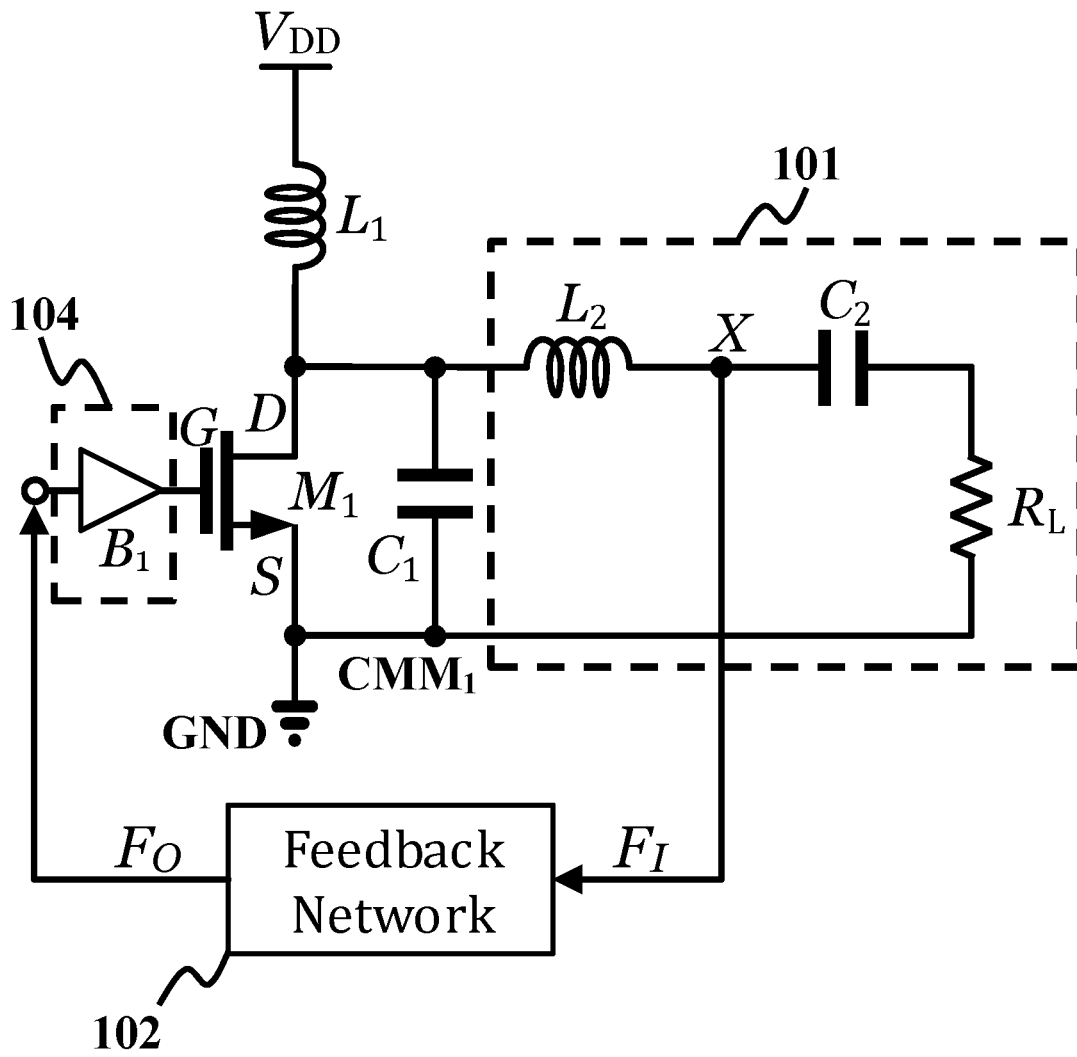


FIG. 1D

100E

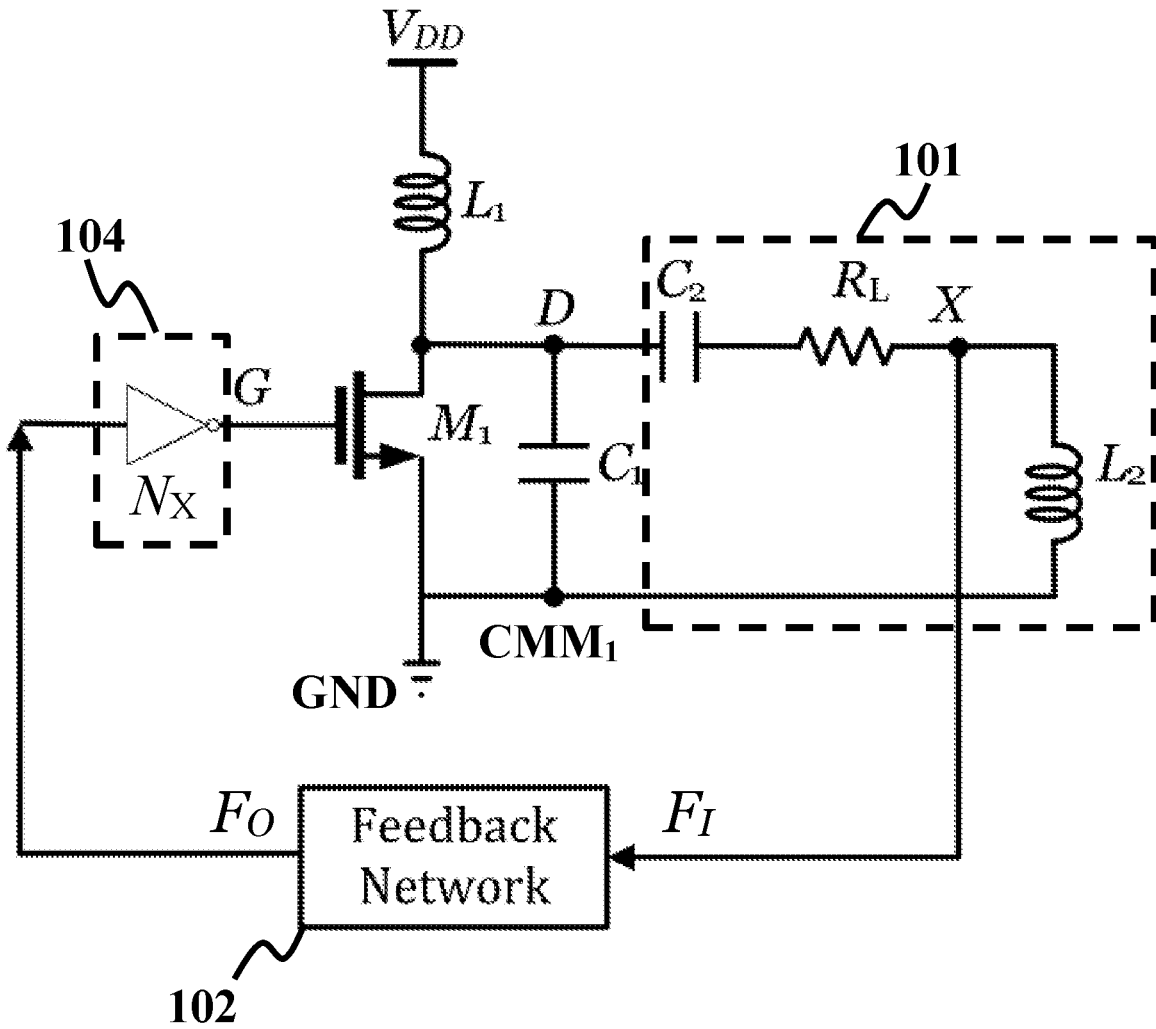


FIG. 1E

100F

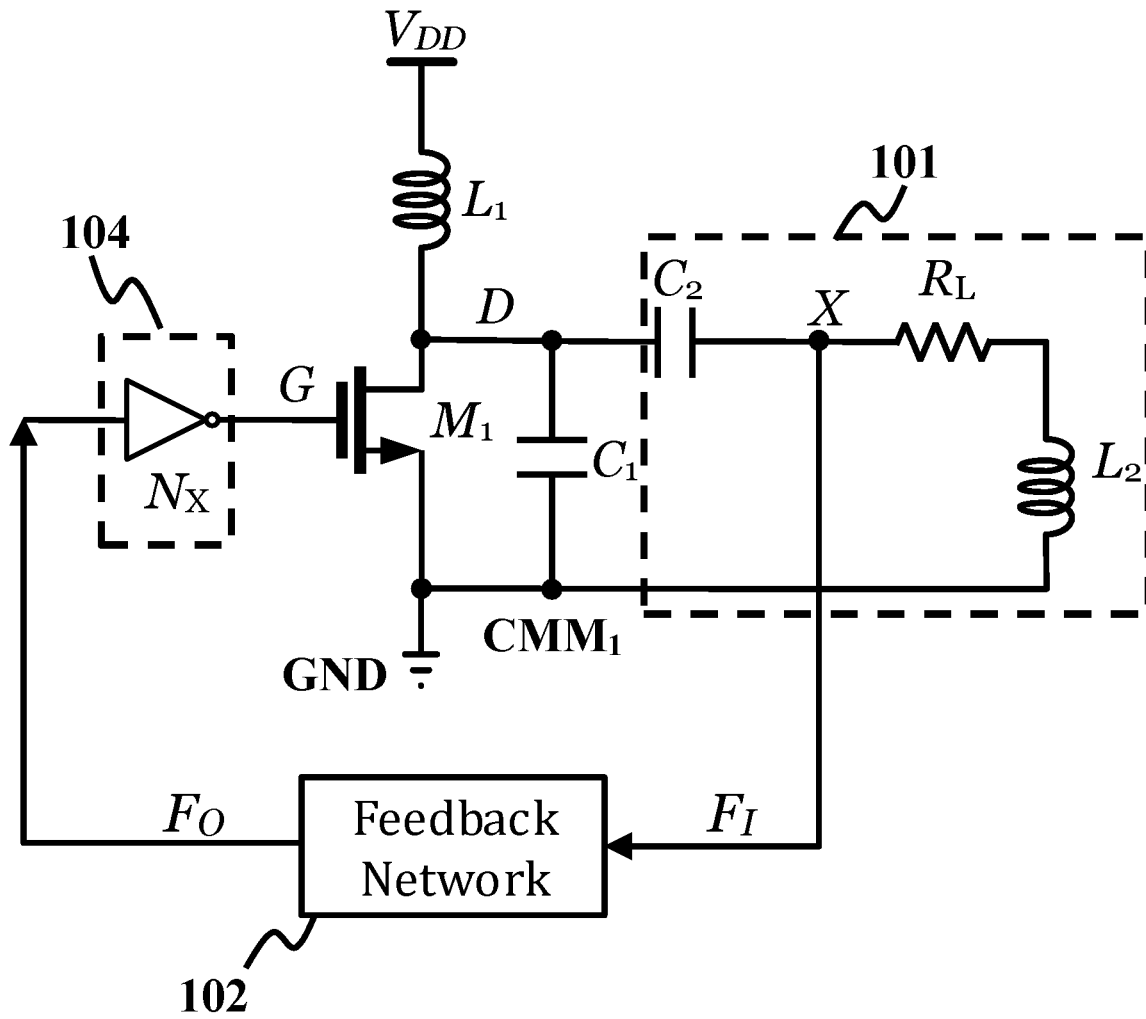


FIG. 1F

100G

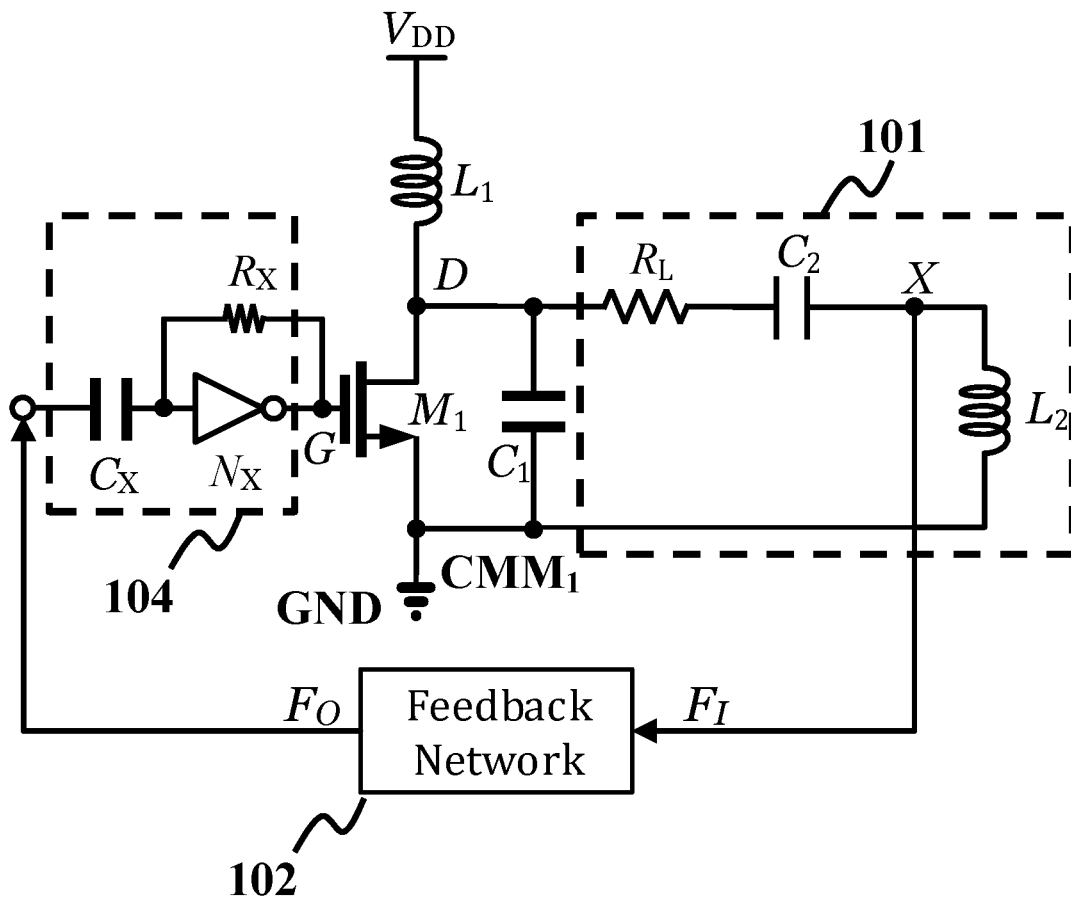


FIG. 1G

102A

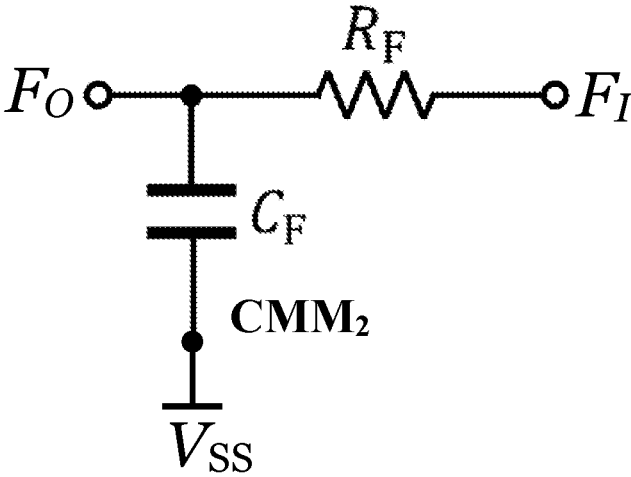


FIG. 2A

102B

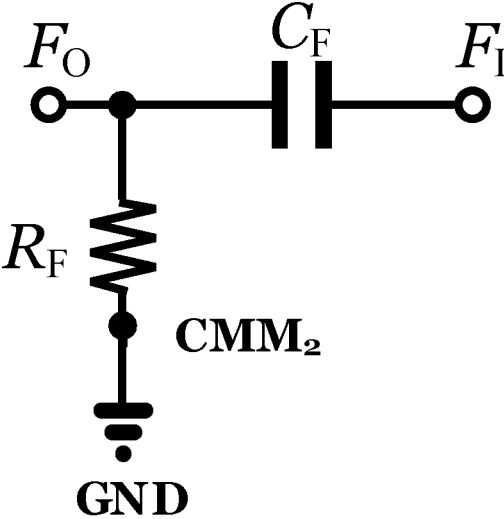


FIG. 2B

102C

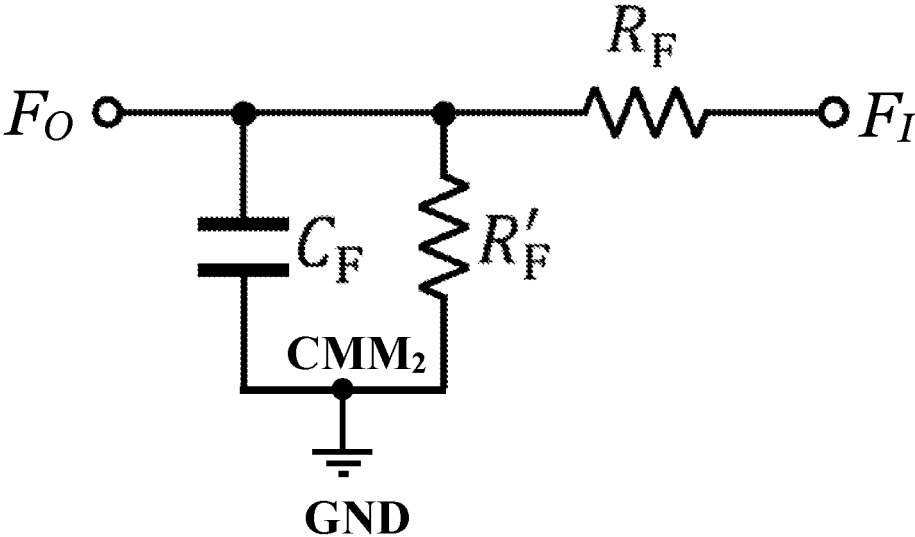


FIG. 2C

102D

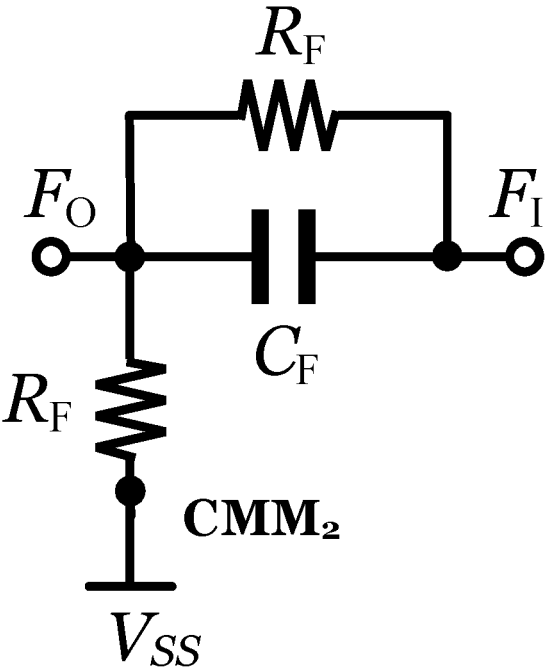


FIG. 2D

102E

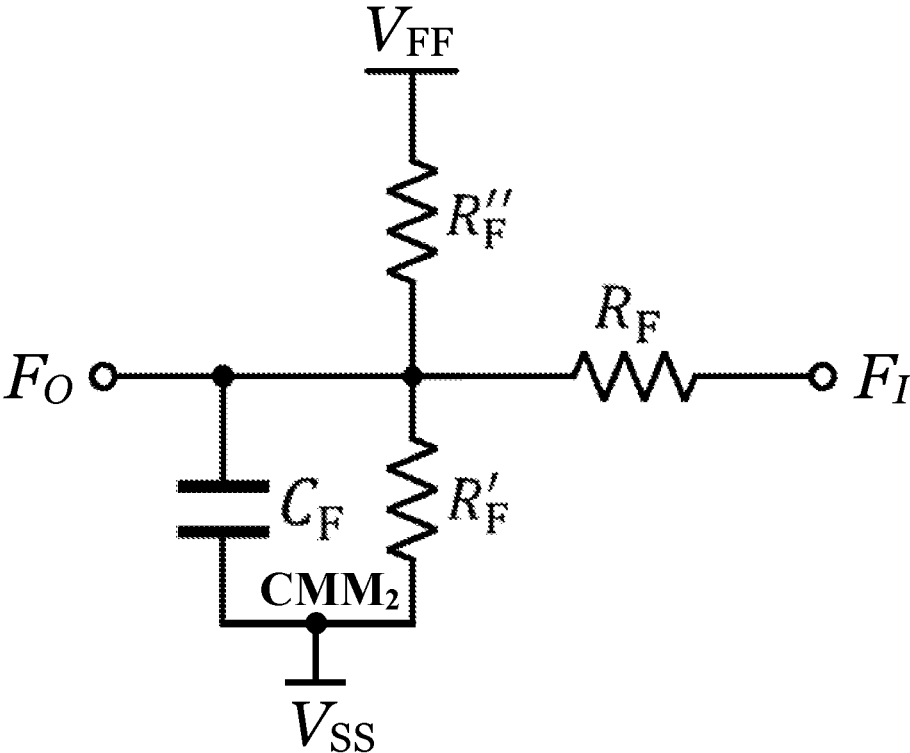


FIG. 2E

102F

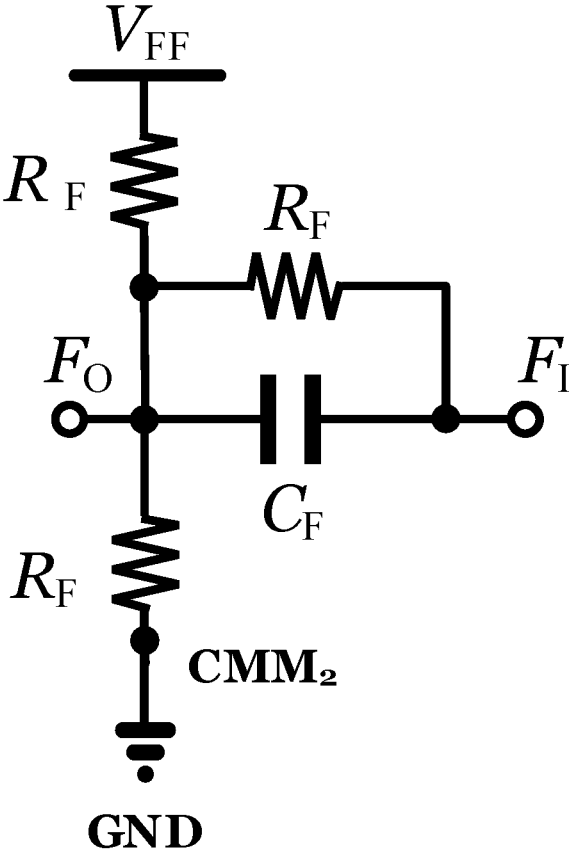


FIG. 2F

300

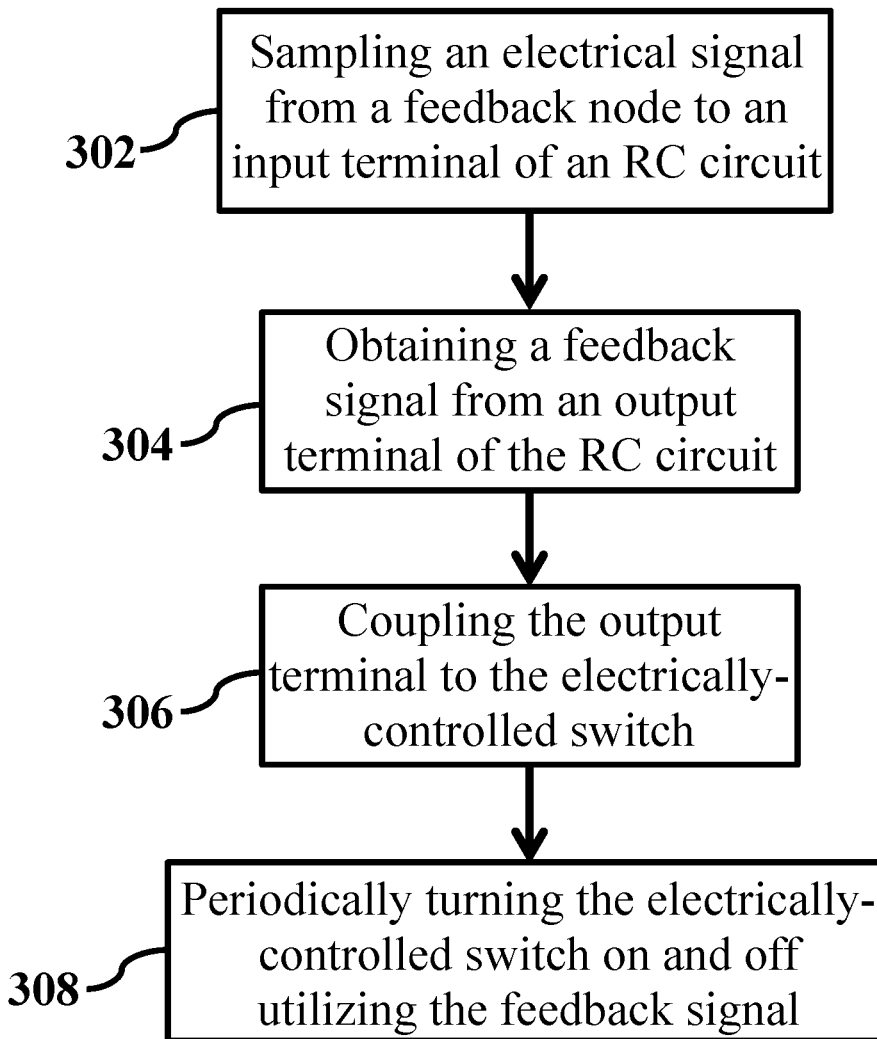


FIG. 3

400

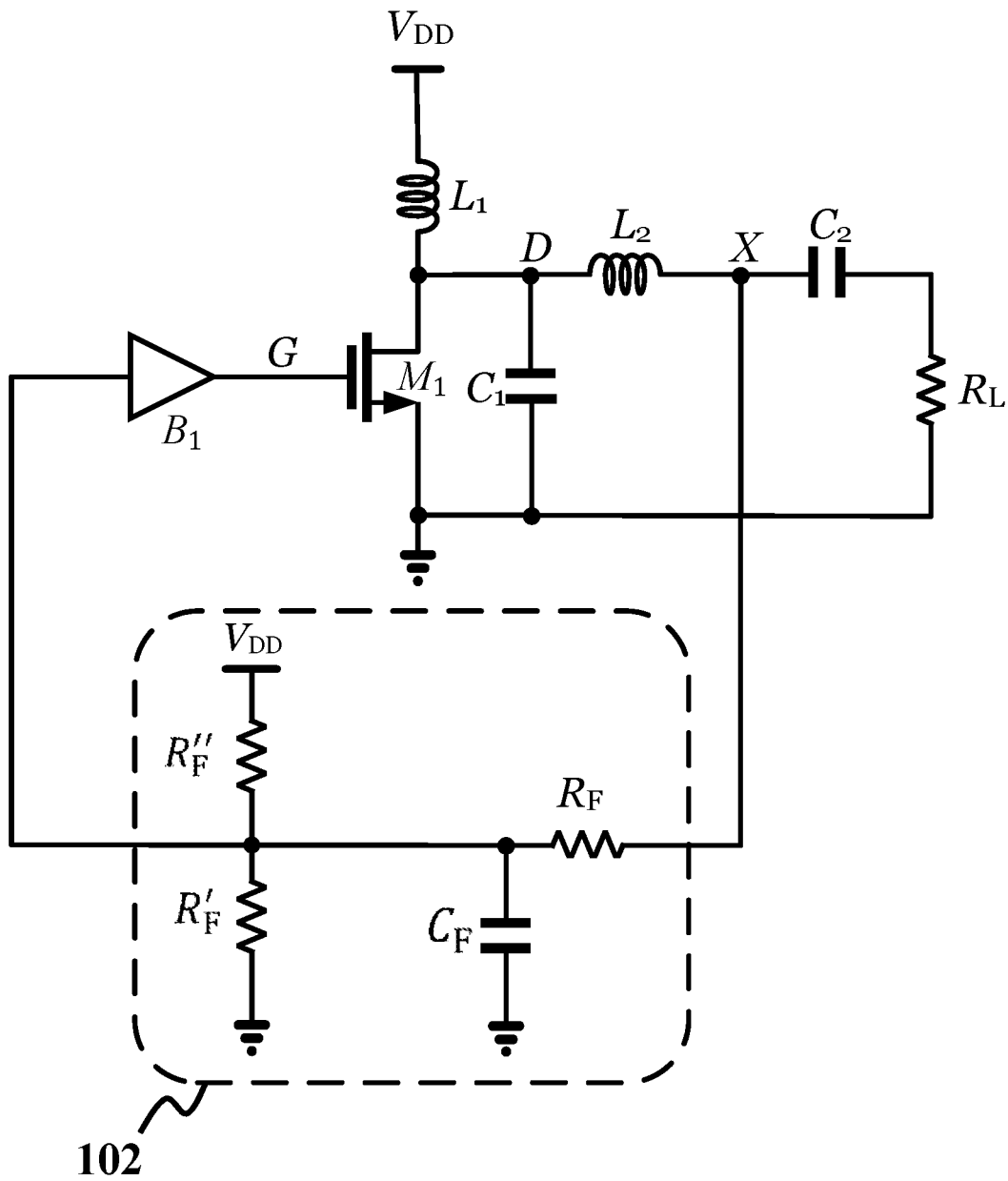


FIG. 4A

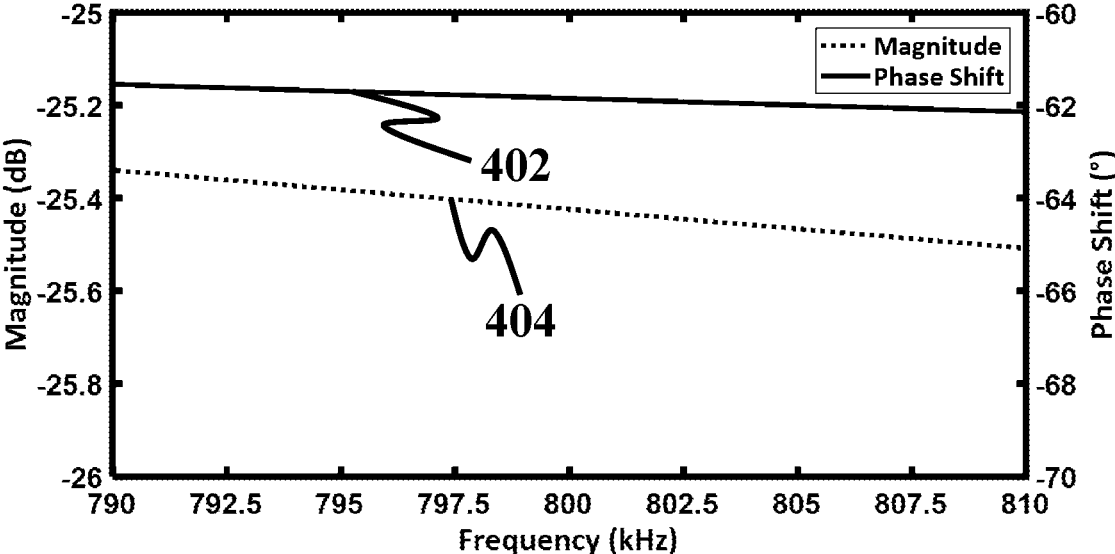


FIG. 4B

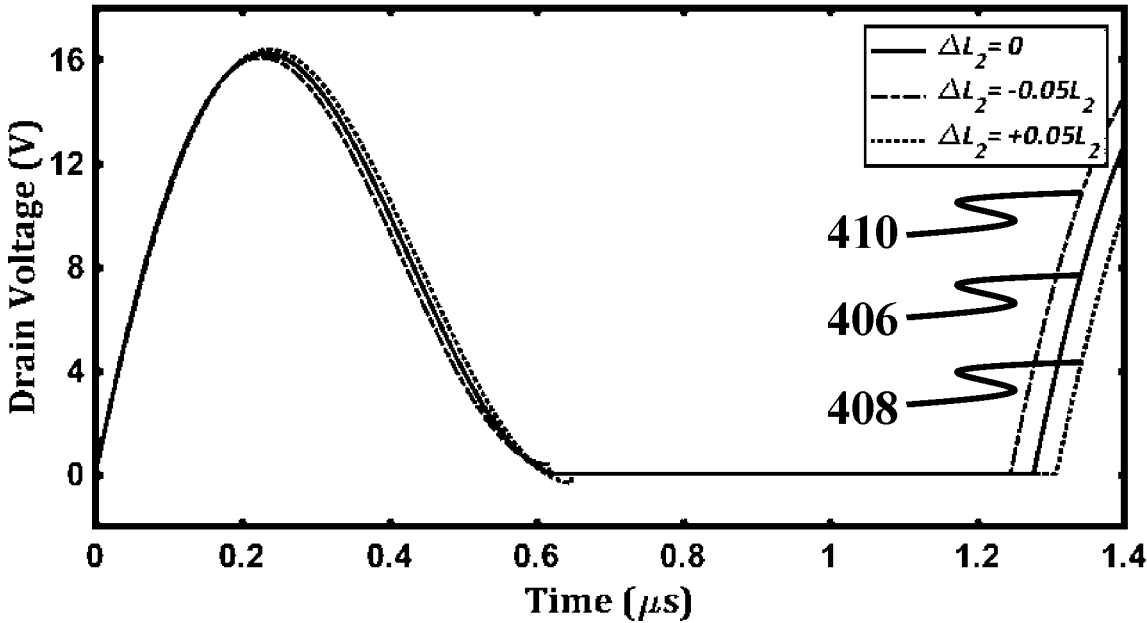


FIG. 4C

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CLASS-E POWER OSCILLATOR**CROSS-REFERENCE TO RELATED APPLICATION**

This application claims the benefit of priority from U.S. Provisional Patent Application Ser. No. 62/701,797, filed on Jul. 22, 2018, and entitled "SELF-TUNED CLASS-E POWER OSCILLATOR," which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

The present disclosure generally relates to power amplifiers, and particularly, to power oscillators.

BACKGROUND

Class-E power amplifiers (PAs) are widely used in numerous applications, including DC/AC inverters, DC/DC converters, wireless communication, and wireless power transfer systems. Class-E PAs, if tuned properly, can achieve high efficiencies. In a class-E PA, values of circuit components should be chosen such that switch waveforms of the class-E PA satisfy zero-voltage switching (ZVS) and zero-voltage-derivative switching (ZVDS) conditions. In such a case, it is said that the class-E PA is in its "nominal" condition. There is only one switching frequency that can maintain the class-E PA at its nominal conditions. This switching frequency is usually called nominal class-E frequency of the PA.

If a mismatch exists between the switching frequency and the nominal class-E frequency, output power and efficiency of the PA may considerably decrease. Small variations in circuit components may result in a frequency mismatch, and consequently significant power loss. To resolve this issue, the switching frequency may be adjusted based on a feedback obtained from an output signal of the PA. Depending on the node from which the feedback signal is obtained, the feedback network may provide a certain amount of phase shift and a certain amount of attenuation (amplification) such that the phase shift in the entire oscillation circuit loop is $-n360^\circ$, where n is a natural number. This may convert the class-E PA to a class-E power oscillator (PO).

There exist a number of issues with conventional class-E POs. First, any change in values of circuit components (including the feedback network components) may cause large degradation in the output power or power efficiency. Second, the phase shift sensitivity of the feedback network to frequency and also to component values in the feedback network may cause the PO to stop oscillation if a value of one of circuit components changes. Third, a high-precision estimate of an input capacitance of a switch of the class-E PO is needed. Fourth, internal switch capacitances may significantly vary in different switches, which makes the estimation difficult and time-consuming, in addition to making the circuit sensitive to a utilized switch.

There is, therefore, a need for a class-E PO with a low sensitivity to variations of component values. There is also a need for a class-E PO with a simple feedback network structure that provides high efficiency and high robustness against design variations of circuit components.

SUMMARY

This summary is intended to provide an overview of the subject matter of the present disclosure, and is not intended

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to identify essential elements or key elements of the subject matter, nor is it intended to be used to determine the scope of the claimed implementations. The proper scope of the present disclosure may be ascertained from the claims set forth below in view of the detailed description below and the drawings.

In one general aspect, the present disclosure describes an exemplary class-E power oscillator (PO). An exemplary class-E PO may include a first inductor, a switch, a first capacitor, a resonant circuit, and a feedback network. The first inductor may be coupled in series to a first power supply. The switch may be connected between the first inductor and a primary common node. The primary common node may be connected to one of a second power supply or ground. The first capacitor may be connected between the first inductor and the primary common node.

In an exemplary embodiment, the resonant circuit may include a second inductor, a second capacitor, and a resistor. The second inductor may be connected between the first inductor and the primary common node. In an exemplary embodiment, the second capacitor may be connected between the first inductor and the primary common node, and may be coupled in series to the second inductor. In an exemplary embodiment, the resistor may be connected between the first inductor and the primary common node, and may be coupled in series to the second inductor. In an exemplary embodiment, the feedback network may be connected between the switch and a feedback node. The feedback node may be located between the second inductor and the second capacitor.

In an exemplary embodiment, the feedback network may include an RC circuit and may be configured to periodically turn the switch on and off based on a resonance frequency of the resonant circuit. An exemplary class-E PO may further include a driver circuit. An exemplary driver circuit may be configured to couple the feedback network to the switch. In an exemplary embodiment, the driver circuit may include a buffer. In an exemplary embodiment, the second inductor may be connected between the first inductor and the feedback node.

In an exemplary embodiment, the driver circuit may include an inverter. In an exemplary embodiment, the second capacitor may be connected between the first inductor and the feedback node. In an exemplary embodiment, the driver circuit may further include a drive resistor and a drive capacitor. In an exemplary embodiment, the drive resistor may be coupled in parallel to the inverter. In an exemplary embodiment, the drive capacitor may be configured to couple the feedback network to the inverter.

In an exemplary embodiment, the switch may include one of a field-effect transistor (FET) or a bipolar junction transistor (BJT). In an exemplary embodiment, the FET may include a metal-oxide-semiconductor field-effect transistor (MOSFET). An exemplary MOSFET may include a gate, a drain, and a source. In an exemplary embodiment, the gate may be connected to an output terminal of the driver circuit. In an exemplary embodiment, the drain may be connected to the first inductor. In an exemplary embodiment, the source may be connected to the primary common node.

In an exemplary embodiment, the BJT may include a base, a collector, and an emitter. In an exemplary embodiment, the base may be connected to an output terminal of the driver circuit. In an exemplary embodiment, the collector may be connected to the first inductor. In an exemplary embodiment, the emitter may be connected to the primary common node.

In an exemplary embodiment, the feedback network may include a feedback input terminal, a feedback output terminal, a first feedback resistor, and a feedback capacitor. An exemplary feedback input terminal may be connected to the feedback node. An exemplary feedback output terminal may be coupled to the driver circuit. In an exemplary embodiment, the feedback capacitor may be connected between the feedback input terminal and a secondary common node. In an exemplary embodiment, the secondary common node may be connected to one of a third power supply or ground. In an exemplary embodiment, the first feedback resistor may be connected between the feedback input terminal and the secondary common node. In an exemplary embodiment, one of the feedback capacitor or the first feedback resistor may be connected between the feedback input terminal and the feedback output terminal. In an exemplary embodiment, one of the feedback capacitor or the first feedback resistor may be connected between the feedback output terminal and the secondary common node.

In an exemplary embodiment, the feedback network may further include a second feedback resistor. The second feedback resistor may be connected in parallel with the feedback capacitor. In an exemplary embodiment, the feedback network may further include a third feedback resistor. In an exemplary embodiment, the third feedback resistor may be connected between the feedback output terminal and a fourth power supply.

Other exemplary systems, methods, features and advantages of the implementations will be, or will become, apparent to one of ordinary skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features and advantages be included within this description and this summary, be within the scope of the implementations, and be protected by the claims herein.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawing figures depict one or more implementations in accord with the present teachings, by way of example only, not by way of limitation. In the figures, like reference numerals refer to the same or similar elements.

FIG. 1A shows a schematic of a class-E power oscillator (PO), consistent with one or more exemplary embodiments of the present disclosure.

FIG. 1B shows a schematic of a class-E power PO in which a second capacitor is connected between a first inductor and a feedback node, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 1C shows a schematic of a class-E power PO with a bipolar junction transistor (BJT) switch, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 1D shows a schematic of a class-E power PO with a field-effect transistor (FET) switch, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 1E shows a schematic of a class-E power PO with a load resistor connected between a second capacitor and second inductor in a resonant circuit, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 1F shows a schematic of a class-E power PO with a feedback node between a second capacitor and a load resistor in a resonant circuit, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 1G shows a schematic of a class-E power PO with a resistor connected between a first inductor and a second

capacitor, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 2A shows a schematic of a first feedback network, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 2B shows a schematic of a second feedback network, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 2C shows a schematic of a third feedback network, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 2D shows a schematic of a fourth feedback network, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 2E shows a schematic of a fifth feedback network, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 2F shows a schematic of a sixth feedback network, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 3 shows a flowchart of a method for reducing sensitivity of a class-E power amplifier (PA), consistent with one or more exemplary embodiments of the present disclosure.

FIG. 4A shows a schematic of a class-E power PO with exemplary specifications, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 4B shows phase and magnitude responses of a feedback network in a class-E power oscillator, consistent with one or more exemplary embodiments of the present disclosure.

FIG. 4C shows drain voltage waveforms of a class-E PO, consistent with one or more exemplary embodiments of the present disclosure.

DETAILED DESCRIPTION

In the following detailed description, numerous specific details are set forth by way of examples in order to provide a thorough understanding of the relevant teachings. However, it should be apparent that the present teachings may be practiced without such details. In other instances, well known methods, procedures, components, and/or circuitry have been described at a relatively high-level, without detail, in order to avoid unnecessarily obscuring aspects of the present teachings.

The following detailed description is presented to enable a person skilled in the art to make and use the methods and devices disclosed in exemplary embodiments of the present disclosure. For purposes of explanation, specific nomenclature is set forth to provide a thorough understanding of the present disclosure. However, it will be apparent to one skilled in the art that these specific details are not required to practice the disclosed exemplary embodiments. Descriptions of specific exemplary embodiments are provided only as representative examples. Various modifications to the exemplary implementations will be readily apparent to one skilled in the art, and the general principles defined herein may be applied to other implementations and applications without departing from the scope of the present disclosure. The present disclosure is not intended to be limited to the implementations shown, but is to be accorded the widest possible scope consistent with the principles and features disclosed herein.

Herein are disclosed exemplary class-E power oscillators and methods for reducing sensitivities of specifications of class-E power oscillators (POs) to values of circuit compo-

nents. An exemplary class-E PO may include an RLC resonant circuit and a low-quality (also called low-Q) RC feedback network. A feedback may be obtained from a node between a capacitor and an inductor of the RLC resonant circuit, where signal amplitude is sufficiently high to feed an electrically-controlled switch through a low-Q RC circuit. By decreasing the quality factor (also called Q-factor) of the RC feedback network by excluding inductive elements (that exist in RLC feedback networks in conventional class-E POs) a phase response of the feedback network may become almost flat around a nominal class-E frequency of an exemplary PO, and if a nominal class-E frequency of the resonant circuit changes due to variations in component values, the phase shift in the feedback network may almost remain unchanged, and therefore, the class-E operation of the circuit may be substantially maintained. As a result, robustness of an exemplary class-E PO against undesired variations in component values may be significantly improved, while power loss may be considerably decreased because of a reduced Q-factor of an exemplary feedback network.

FIG. 1A shows a schematic of a class-E power oscillator (PO), consistent with one or more exemplary embodiments of the present disclosure. An exemplary class-E PO 100A may include a first inductor L_1 , a switch M_1 , a first capacitor C_1 , a resonant circuit 101, and a feedback network 102. In an exemplary embodiment, first inductor L_1 may be coupled in series to a first power supply V_{DD} . In an exemplary embodiment, switch M_1 may be connected between first inductor L_1 and a primary common node CMM_1 . In an exemplary embodiment, first capacitor C_1 may be connected between first inductor L_1 and primary common node CMM_1 .

In an exemplary embodiment, resonant circuit 101 may include a second inductor L_2 , a second capacitor C_2 , and a load resistor R_L . In an exemplary embodiment, second inductor L_2 may be connected between the first inductor L_1 and primary common node CMM_1 . In an exemplary embodiment, second capacitor C_2 may be connected between first inductor L_1 and primary common node CMM_1 , and may be coupled in series to second inductor L_2 . In an exemplary embodiment, load resistor R_L may be connected between first inductor L_1 and primary common node CMM_1 , and may be coupled in series to second inductor L_2 . In an exemplary embodiment, feedback network 102 may be connected between switch M_1 and a feedback node X. In an exemplary embodiment, feedback node X may be located between second inductor L_2 and second capacitor C_2 . In an exemplary embodiment, an electrical signal at this node may have a large amplitude.

In an exemplary embodiment, feedback network 102 may include an RC circuit and may be configured to periodically turn switch M_1 on and off based on a resonance frequency of resonant circuit 101. In an exemplary embodiment, a switching period of switch M_1 may be determined based on an inverse of the resonance frequency. In an exemplary embodiment, an electrical signal at feedback node X may be fed to feedback network 102 at a feedback input terminal F_I of feedback network 102 to obtain a feedback signal at a feedback output terminal F_O of feedback network 102. In an exemplary embodiment, switch M_1 may turn on when an amplitude of the feedback signal exceeds a switching threshold (determined based on a type or a structure of switch M_1) at each switching period of switch M_1 , and may turn off when the amplitude of the feedback signal decreases below the switching threshold. In an exemplary embodiment, feedback network 102 may include an RC circuit, which may provide a feedback network with a low Q-factor by excluding inductive elements (that exist in RLC feedback networks

in conventional class-E POs) from feedback network 102. As a result, in an exemplary embodiment, the phase shift of feedback network 102, and consequently, power loss of class-E PO 100 may be considerably decreased because of a reduced Q-factor of feedback network 102, thereby increasing efficiency of class-E PO 100.

In an exemplary embodiment, class-E PO 100A may further include a driver circuit 104. In an exemplary embodiment, driver circuit 104 may be configured to couple feedback network 102 to switch M_1 . In an exemplary embodiment, using a gate driver may simplify designing class-E PO 100 and may improve the performance of the class-E PO 100 as it may buffer nonlinear capacitance of switch M_1 , which may be difficult to model. In an exemplary embodiment, driver circuit 104 may include a buffer B_1 . In an exemplary embodiment, second inductor L_2 may be connected between first inductor L_1 and feedback node X.

FIG. 1B shows a schematic of a class-E power PO 100B in which second capacitor C_1 is connected between first inductor L_1 and feedback node X, consistent with one or more exemplary embodiments of the present disclosure. In an exemplary embodiment, driver circuit 104 may include an inverter N_X . In an exemplary embodiment, driver circuit 104 may further include a drive resistor R_X and a drive capacitor C_X . In an exemplary embodiment, drive resistor R_X may be coupled in parallel to inverter N_X . In an exemplary embodiment, drive capacitor C_X may be configured to couple feedback network 102 to inverter N_X . In an exemplary embodiment, inverter N_X may be used to drive switch M_1 . In an exemplary embodiment, drive resistor R_X may help class-E PO 100 start oscillating autonomously. In an exemplary embodiment, drive capacitor C_X may be much larger than an input capacitance of driver circuit 104. In an exemplary embodiment, drive capacitor C_X may decouple a DC bias of an output node of feedback network 102 from a DC bias of an input node of inverter N_X . In an exemplary embodiment, employing drive resistor R_X and drive capacitor C_X may minimize requirements of feedback network 102 circuit and may simplify an oscillation start-up in class-E PO 100.

FIG. 1C shows a schematic of a class-E PO 100C with a bipolar junction transistor (BJT) switch, consistent with one or more exemplary embodiments of the present disclosure. In an exemplary embodiment, switch M_1 may include a BJT. In an exemplary embodiment, the BJT may include a base B, a collector C, and an emitter E. In an exemplary embodiment, base B may be connected to an output terminal of driver circuit 104. In an exemplary embodiment, collector C may be connected to first inductor L_1 . In an exemplary embodiment, emitter E may be connected to a ground node GND via primary common node CMM_1 .

FIG. 1D shows a schematic of a class-E power PO 100D with a field-effect transistor (FET) switch, consistent with one or more exemplary embodiments of the present disclosure. In an exemplary embodiment, the FET may include a metal-oxide-semiconductor field-effect transistor (MOSFET). An exemplary MOSFET may include a gate G, a drain D, and a source S. In an exemplary embodiment, gate G may be connected to an output terminal of driver circuit 104. In an exemplary embodiment, drain D may be connected to first inductor L_1 . In an exemplary embodiment, source S may be connected to ground node GND via primary common node CMM_1 .

In an exemplary embodiment, in a nominally-tuned Class-E PA or PO, a phase shift between fundamental components of the gate and drain signals of the MOSFET may be about -163.6° . This value is for the case that the duty

cycle of the gate drive signal is about 50%. If the duty cycle is different from 50%, the phase shift may be different. For example, if the duty cycle is about 60%, the phase shift may be about -166.4° . At the same time, the phase shift from drain D to feedback node X, depending on the Q-factor and the value of L_1/L_2 , may be in a range of about 50° to about 80° . Therefore, a feedback network that includes a single-pole RC circuit may provide enough phase shift to convert a Class-E PA to a Class-E PO.

FIG. 1E shows a schematic of a class-E power PO **100E** with load resistor R_L connected between second capacitor C_2 and second inductor L_2 in resonant circuit **101**, consistent with one or more exemplary embodiments of the present disclosure. In an exemplary embodiment, feedback node X may be located between load resistor R_1 , and second inductor L_2 . In an exemplary embodiment, if class-E PO **100E** is nominally tuned, a phase shift from drain D to feedback node X may be in a range of about $+37.8^\circ$ and about $+45.2^\circ$, depending on the Q-factor and the value of L_1/L_2 . In an exemplary embodiment, if the duty cycle of the gate drive signal is about 50%, the phase shift from gate G to drain D may be about -163.6° . Therefore, in an exemplary embodiment, the phase shift from gate G to feedback node X may be between about -118.4° and about -125.8° , if the duty cycle of the gate drive signal is about 50%. As a result, feedback network **102** may provide a phase shift between about -234.4° and about -241.8° . In an exemplary embodiment, this amount of phase shift may be provided with an RC circuit that includes at least three capacitors (to generate a circuit with three frequency poles). Alternatively, inverter N_X along with a single-pole RC circuit, may be utilized to provide the aforementioned amount of phase shift. In an exemplary embodiment, inverter N_X may provide a phase shift of at least -180° , therefore the remainder of the phase shift, which may be between about -54.4° and about -61.8° , may be generated with a simple single-pole circuit.

FIG. 1F shows a schematic of a class-E power PO **100F** with feedback node X between second capacitor C_2 and load resistor R_L in resonant circuit **101**, consistent with one or more exemplary embodiments of the present disclosure. In an exemplary embodiment, similar to class-E power PO **100E** in FIG. 1E, feedback network **102** may include either a three-pole RC circuit or a single-pole RC circuit along with inverter N_X .

FIG. 1G shows a schematic of a class-E power PO **100G** with load resistor R_L connected between first inductor L_1 and second capacitor C_2 , consistent with one or more exemplary embodiments of the present disclosure. In an exemplary embodiment, feedback network **102** may include either a three-pole RC circuit, or a single-pole RC circuit along with driver circuit **104**. In an exemplary embodiment, load resistor R_L may be placed in different locations in resonant circuit **101**, and exemplary class-E power POs may show similar performances as long as feedback node X is located between second inductor L_2 and second capacitor C_2 .

FIG. 2A shows a schematic of a first feedback network, consistent with one or more exemplary embodiments of the present disclosure. An exemplary first feedback network **102A** may include an implementation of feedback network **102**. In an exemplary embodiment, first feedback network **102A** may include a feedback input terminal F_1 , a feedback output terminal F_O , a first feedback resistor R_F , and a feedback capacitor C_F . In an exemplary embodiment, feedback input terminal F_1 may be connected to feedback node X. In an exemplary embodiment, feedback output terminal F_O may be coupled to driver circuit **104**. In an exemplary embodiment, feedback capacitor C_F may be connected

between feedback input terminal F_1 and a secondary common node CMM_2 . In an exemplary embodiment, secondary common node CMM_2 may be connected to one of a third power supply V_{SS} or ground node GND. In an exemplary embodiment, first feedback resistor R_F may be connected between feedback input terminal F_1 and secondary common node CMM_2 . In an exemplary embodiment, one of feedback capacitor C_F or first feedback resistor R_F may be connected between feedback input terminal F_1 and feedback output terminal F_O . In an exemplary embodiment, one of feedback capacitor C_F or first feedback resistor R_F may be connected between feedback output terminal F_O and secondary common node CMM_2 . For example, as shown in FIG. 2A, first feedback resistor R_F may be connected between feedback input terminal F_1 and feedback output terminal F_O , and feedback capacitor C_F may be connected between feedback output terminal F_O and secondary common node CMM_2 .

FIG. 2B shows a schematic of a second feedback network, consistent with one or more exemplary embodiments of the present disclosure. An exemplary second feedback network **102B** may include an implementation of first feedback network **102A**. In an exemplary embodiment, as shown in FIG. 2B, feedback capacitor C_F may be connected between feedback input terminal F_1 and feedback output terminal F_O and first feedback resistor R may be connected between feedback output terminal F_O and secondary common node CMM_2 .

FIG. 2C shows a schematic of a third feedback network, consistent with one or more exemplary embodiments of the present disclosure. An exemplary third feedback network **102C** may include an implementation of feedback network **102**. In an exemplary embodiment, third feedback network **102C** may include elements similar to those of first feedback network **102A**. In an exemplary embodiment, third feedback network **102C** may further include a second feedback resistor R'_F . In an exemplary embodiment, second feedback resistor R'_F may be connected in parallel with feedback capacitor C_F . In an exemplary embodiment, adding second feedback resistor R'_F to first feedback network **102A** may attenuate a signal amplitude at feedback node X, thereby preventing damage to switch M_1 .

FIG. 2D shows a schematic of a fourth feedback network, consistent with one or more exemplary embodiments of the present disclosure. An exemplary fourth feedback network **102D** may include an implementation of feedback network **102**. In an exemplary embodiment, fourth feedback network **102D** may include elements similar to those of second feedback network **102B**. In an exemplary embodiment, third feedback network **102C** may further include second feedback resistor R'_F . In an exemplary embodiment, second feedback resistor R'_F may be connected in parallel with feedback capacitor C_F . In an exemplary embodiment, adding second feedback resistor R'_F to second feedback network **102B** may attenuate a signal amplitude at feedback node X, thereby preventing damage to switch M_1 .

FIG. 2E shows a schematic of a fifth feedback network, consistent with one or more exemplary embodiments of the present disclosure. An exemplary fifth feedback network **102E** may include an implementation of feedback network **102**. In an exemplary embodiment, fifth feedback network **102E** may include elements similar to those of third feedback network **102C**. In an exemplary embodiment, fifth feedback network **102E** may further include a third feedback resistor R''_F . In an exemplary embodiment, third feedback resistor R''_F may be connected between feedback output terminal F_O and a fourth power supply V_{FF} . In an exemplary embodiment, fourth power supply V_{FF} may provide similar

voltage as first power supply V_{DD} , or may provide a different voltage. In an exemplary embodiment, adding third feedback resistor R_F to third feedback network **102C** may provide enough flexibility to adjust phase shift, DC level, and amplitude of a signal at feedback output terminal F_O . Adjusting the DC signal level at feedback output terminal F_O may help in determining a duty cycle of the switch M_1 drive signal.

FIG. 2F shows a schematic of a sixth feedback network, consistent with one or more exemplary embodiments of the present disclosure. An exemplary sixth feedback network **102F** may include an implementation of feedback network **102**. In an exemplary embodiment, sixth feedback network **102F** may include elements similar to those of fourth feedback network **102D**. In an exemplary embodiment, sixth feedback network **102F** may further include third feedback resistor R_F . In an exemplary embodiment, third feedback resistor R_F may be connected between feedback output terminal F_O and fourth power supply V_{FF} . In an exemplary embodiment, fourth power supply V_{FF} may provide similar voltage as first power supply V_{DD} , or may provide a different voltage. In an exemplary embodiment, adding third feedback resistor R_F to third feedback network **102D** may provide enough flexibility to adjust phase shift, DC level, and amplitude of a signal that drives switch M_1 . Adjusting the DC signal level at feedback output terminal F_O may help in determining a duty cycle of the switch M_1 drive signal.

FIG. 3 shows a flowchart of a method for reducing sensitivity of a class-E power amplifier (PA), consistent with one or more exemplary embodiments of the present disclosure. An exemplary class-E PA may include an electrically-controlled switch and a resonant circuit. Referring to FIGS. 1A-1D, in an exemplary embodiment, the electrically-controlled switch may be analogous to switch M_1 , and the resonant circuit may be analogous to resonant circuit **101**. In an exemplary embodiment, the resonant circuit may include an inductor and a capacitor that may be coupled in series. In an exemplary embodiment, the inductor may be analogous to second inductor L_2 and the capacitor may be analogous to second capacitor C_2 . An exemplary method **300** may include feeding an electrical signal from a feedback node to an input terminal of an RC circuit (step **302**), obtaining a feedback signal from an output terminal of the RC circuit (step **304**), coupling the output terminal to the electrically-controlled switch (step **306**), and periodically turning the electrically-controlled switch on and off utilizing the feedback signal based on a resonance frequency of the resonant circuit (step **308**). In an exemplary embodiment, the feedback node may be analogous to feedback node X and may be located between the capacitor and the inductor. In an exemplary embodiment, the RC circuit may be analogous to feedback network **102**.

EXAMPLE

In this example, performance of an exemplary class-E PO analogous to class-E PO **100** is demonstrated. FIG. 4A shows a schematic of a class-E power PO **400** with exemplary specifications, consistent with one or more exemplary embodiments of the present disclosure. Table 1 shows a list of specifications and approximate component values for which class-E power PO **400** is designed. An FQT13n061 transistor is used for implementing switch M_1 and a 74AC244 buffer is used for implementing buffer B_1 .

TABLE 1

Output Power, P_O	1.0 W
Supply Voltage, V_{DD}	4.5 V
Operating Frequency, f_c	800 kHz
Loaded Q-Factor, Q_L	13
L_1	0.9 mH
L_2	27.74 mH
C_1	3.56 nF
C_2	1565 pF
R_L	10.3 Ω
R_F	30.9 k Ω
R'_F	7 k Ω
R''_F	9.1 k Ω
C_F	106 pF

FIG. 4B shows phase and magnitude responses of a feedback network in class-E PO **400**, consistent with one or more exemplary embodiments of the present disclosure. Variations in a phase shift **402** of feedback network **102** is less than about 0.5° in a frequency range of about 790 kHz to about 810 kHz. Also, a change in a magnitude response **404** of feedback network **102** is less than about 0.2 dB, which indicates high robustness against variations in the component values of Class-E PO **400**.

FIG. 4C shows drain voltage waveforms of class-E PO **400**, consistent with one or more exemplary embodiments of the present disclosure. A waveform **406** shows a voltage waveform of drain D for a nominal value of second inductor L_2 , i.e., zero variation ΔL_2 in the inductance of second inductor L_2 . Waveforms **408** and **410** show voltage waveforms of drain D for $\Delta L_2 = 0.05L_2$ and $\Delta L_2 = -0.05L_2$, respectively. When L_2 and other components have their nominal value, an output power and power efficiency are respectively about 1 W and about 95%. Major sources of power loss in this case are an equivalent series resistance (ESR) of L_2 , an on-resistance of switch M_1 , and an AC power loss in feedback network **102**.

When L_2 increases by about 5%, the output power decreases by only about 3.12% and the efficiency changes by only about -0.1% . When L_2 decreases by 5%, the output power increases by only about 3.55% and the power efficiency changes by only about 0.37%. This experiment demonstrates resilience of class-E PO **400** against changes in the value of L_2 . As seen here, the output power and the power efficiency of the class-E PO **400** have very small sensitivity to the value of L_2 . Similarly, class-E PO **400** has small sensitivities to values of other circuit components.

Advantages of class-E PO **400** are due to the fact that feedback network **102** is a low-Q circuit, in which phase response **402** and magnitude response **404**, as shown FIG. 4B, are almost flat around the class-E frequency, and if the class-E frequency changes for whatever reason, the change in the phase and magnitude of transfer function of feedback network **102** may be very small and the power oscillator may stay close to its nominal class-E operation. In addition, because feedback network **102** is not a resonant circuit, it does not have a specific resonance frequency that may interfere with the resonance and the class-E frequency of class-E PO **400**. As a result, the output power and the efficiency of class-E PO **400** have negligible sensitivities to component variations and if the values of the circuit components change, the circuit may move towards its nominal class-E operation.

While the foregoing has described what may be considered to be the best mode and/or other examples, it is understood that various modifications may be made therein and that the subject matter disclosed herein may be implemented in various forms and examples, and that the teach-

ings may be applied in numerous applications, only some of which have been described herein. It is intended by the following claims to claim any and all applications, modifications and variations that fall within the true scope of the present teachings.

Unless otherwise stated, all measurements, values, ratings, positions, magnitudes, sizes, and other specifications that are set forth in this specification, including in the claims that follow, are approximate, not exact. They are intended to have a reasonable range that is consistent with the functions to which they relate and with what is customary in the art to which they pertain.

The scope of protection is limited solely by the claims that now follow. That scope is intended and should be interpreted to be as broad as is consistent with the ordinary meaning of the language that is used in the claims when interpreted in light of this specification and the prosecution history that follows and to encompass all structural and functional equivalents. Notwithstanding, none of the claims are intended to embrace subject matter that fails to satisfy the requirement of Sections 101, 102, or 103 of the Patent Act, nor should they be interpreted in such a way. Any unintended embracement of such subject matter is hereby disclaimed.

Except as stated immediately above, nothing that has been stated or illustrated is intended or should be interpreted to cause a dedication of any component, step, feature, object, benefit, advantage, or equivalent to the public, regardless of whether it is or is not recited in the claims.

It will be understood that the terms and expressions used herein have the ordinary meaning as is accorded to such terms and expressions with respect to their corresponding respective areas of inquiry and study except where specific meanings have otherwise been set forth herein. Relational terms such as first and second and the like may be used solely to distinguish one entity or action from another without necessarily requiring or implying any actual such relationship or order between such entities or actions. The terms “comprises,” “comprising,” or any other variation thereof, are intended to cover a non-exclusive inclusion, such that a process, method, article, or apparatus that comprises a list of elements does not include only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. An element preceded by “a” or “an” does not, without further constraints, preclude the existence of additional identical elements in the process, method, article, or apparatus that comprises the element.

The Abstract of the Disclosure is provided to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. In addition, in the foregoing Detailed Description, it can be seen that various features are grouped together in various implementations. This is for purposes of streamlining the disclosure, and is not to be interpreted as reflecting an intention that the claimed implementations require more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive subject matter lies in less than all features of a single disclosed implementation. Thus, the following claims are hereby incorporated into the Detailed Description, with each claim standing on its own as a separately claimed subject matter.

While various implementations have been described, the description is intended to be exemplary, rather than limiting and it will be apparent to those of ordinary skill in the art that many more implementations and implementations are pos-

sible that are within the scope of the implementations. Although many possible combinations of features are shown in the accompanying figures and discussed in this detailed description, many other combinations of the disclosed features are possible. Any feature of any implementation may be used in combination with or substituted for any other feature or element in any other implementation unless specifically restricted. Therefore, it will be understood that any of the features shown and/or discussed in the present disclosure may be implemented together in any suitable combination. Accordingly, the implementations are not to be restricted except in light of the attached claims and their equivalents. Also, various modifications and changes may be made within the scope of the attached claims.

What is claimed is:

1. A class-E power oscillator (PO), comprising:
 - a first inductor coupled in series to a first power supply;
 - a switch connected between the first inductor and a primary common node, the primary common node connected to one of a second power supply or ground;
 - a first capacitor connected between the first inductor and the primary common node;
 - a resonant circuit comprising:
 - a second inductor connected between the first inductor and the primary common node;
 - a second capacitor connected between the first inductor and the primary common node, the second capacitor coupled in series to the second inductor; and
 - a resistor connected between the first inductor and the primary common node, the resistor coupled in series to the second inductor and the second capacitor; and
 - a feedback network connected between the switch and a feedback node located between the second inductor and the second capacitor, the feedback network comprising an RC circuit, the feedback network configured to periodically turn the switch on and off based on a resonance frequency of the resonant circuit;
 - wherein the resistor, the second inductor, and the second capacitor are connected in series.
2. The class-E PO of claim 1, further comprising a driver circuit configured to couple the feedback network to the switch.
3. The class-E PO of claim 2, wherein:
 - the driver circuit comprises a buffer; and
 - the second inductor is connected between the first inductor and the feedback node.
4. The class-E PO of claim 2, wherein the driver circuit comprises an inverter.
5. The class-E PO of claim 4, wherein the second capacitor is connected between the first inductor and the feedback node.
6. The class-E PO of claim 4, wherein the driver circuit further comprises:
 - a drive resistor coupled in parallel to the inverter; and
 - a drive capacitor configured to couple the feedback network to the inverter.
7. The class-E PO of claim 1, wherein the switch comprises one of a field-effect transistor (FET) or a bipolar junction transistor (BJT).
8. The class-E PO of claim 7, wherein the FET comprises a metaloxide-semiconductor field-effect transistor (MOSFET), the MOSFET comprising:
 - a gate connected to an output terminal of the driver circuit;
 - a drain connected to the first inductor; and
 - a source connected to the primary common node.

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9. The class-E PO of claim 7, wherein the BJT comprises:
 a base connected to an output terminal of the driver
 circuit;

a collector connected to the first inductor; and
 an emitter connected to the primary common node.

10. The class-E PO of claim 1, wherein the feedback
 network comprises:

a feedback input terminal connected to the feedback node;
 a feedback output terminal connected to the driver circuit;
 a feedback capacitor connected between the feedback
 input terminal and a secondary common node, the
 secondary common node connected to one of a third
 power supply or ground; and

a first feedback resistor connected between the feedback
 input terminal and the secondary common node;

wherein:

one of the feedback capacitor or the first feedback
 resistor is connected between the feedback input
 terminal and the feedback output terminal; and

one of the feedback capacitor or the first feedback
 resistor is connected between the feedback output
 terminal and the secondary common node.

11. The class-E PO of claim 10, wherein the feedback
 network further comprises a second feedback resistor con-
 nected in parallel with the feedback capacitor.

12. The class-E PO of claim 11, wherein the feedback
 network further comprises a third feedback resistor con-
 nected between the feedback output terminal and a fourth
 power supply.

13. A method for reducing sensitivity of a class-E power
 amplifier (PA) comprising an electrically-controlled switch
 and a resonant circuit, the resonant circuit comprising an
 inductor and a capacitor coupled in series, the method
 comprising:

coupling a resistor in series to the inductor in the resonant
 circuit;

coupling the resistor in series to the capacitor in the
 resonant circuit;

feeding an electrical signal from a feedback node located
 between the capacitor and the inductor to an input
 terminal of a feedback network;

obtaining a feedback signal from an output terminal of the
 RC circuit;

coupling the output terminal to the electrically-controlled
 switch; and

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periodically turning the electrically-controlled switch on
 and off utilizing the feedback signal based on a reso-
 nance frequency of the resonant circuit.

14. The method of claim 13, wherein obtaining the
 feedback signal from the output terminal of the feedback
 network comprises:

connecting a first feedback resistor between the input
 terminal and the output terminal;

connecting a feedback capacitor between the output ter-
 minal and ground;

connecting a second feedback resistor between the output
 terminal and ground; and

connecting a third feedback resistor between the output
 terminal and a power supply.

15. The method of claim 13, wherein obtaining the
 feedback signal from the output terminal of the feedback
 network comprises:

connecting a feedback capacitor between the input termi-
 nal and the output terminal;

connecting a first feedback resistor between the output
 terminal and ground;

connecting a second feedback resistor between the input
 terminal and the output terminal; and

connecting a third feedback resistor between the output
 terminal and a power supply.

16. The method of claim 13, further comprising coupling
 the output terminal to the electrically-controlled switch
 through a buffer.

17. The method of claim 13, further comprising coupling
 the output terminal to the electrically-controlled switch
 through a driver circuit comprising:

an inverter;

a drive resistor coupled in parallel to the inverter; and

a drive capacitor connected between the output terminal
 and the inverter.

18. The method of claim 13, wherein coupling the output
 terminal to the electrically-controlled switch comprises cou-
 pling the output terminal to one of a gate of a field-effect
 transistor (FET) or a base of a bipolar junction transistor
 (BJT).

19. The method of claim 13, wherein feeding the electrical
 signal from the feedback node to the input terminal of the
 feedback network comprises feeding the electrical signal to
 an input terminal of an RC circuit.

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