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(54) **RADIO FREQUENCY OSCILLATOR**

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051574, filed on Jan. 27, 2015.

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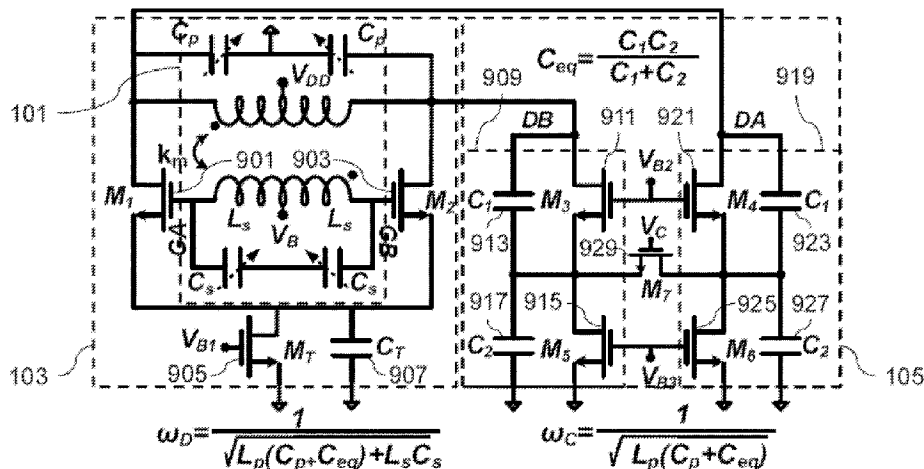*H03B 5/12* (2006.01)
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(57) **ABSTRACT**
The embodiments of the invention relate to a radio fre-
quency oscillator, the radio frequency oscillator comprising
a resonator circuit resonant at an excitation of the resonator
circuit in a differential mode and at an excitation of the
resonator circuit in a common mode, wherein the resonator
circuit has a differential mode resonance frequency at the
excitation in the differential mode, and wherein the resonator
circuit has a common mode resonance frequency at the
excitation in the common mode, a first excitation circuit
configured to excite the resonator circuit in the differential
mode to obtain a differential mode oscillator signal oscil-
lating at the differential mode resonance frequency, and a
second excitation circuit configured to excite the resonator
circuit in the common mode to obtain a common mode
oscillator signal oscillating at the common mode resonance
frequency.

17 Claims, 10 Drawing Sheets

$$\omega_D = \frac{1}{\sqrt{L_p(C_{p+}C_{eq})}+L_sC_s}$$

$$\omega_C = \frac{1}{\sqrt{L_p(C_p+C_{eq})}}$$

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  H03F 3/72 (2006.01)
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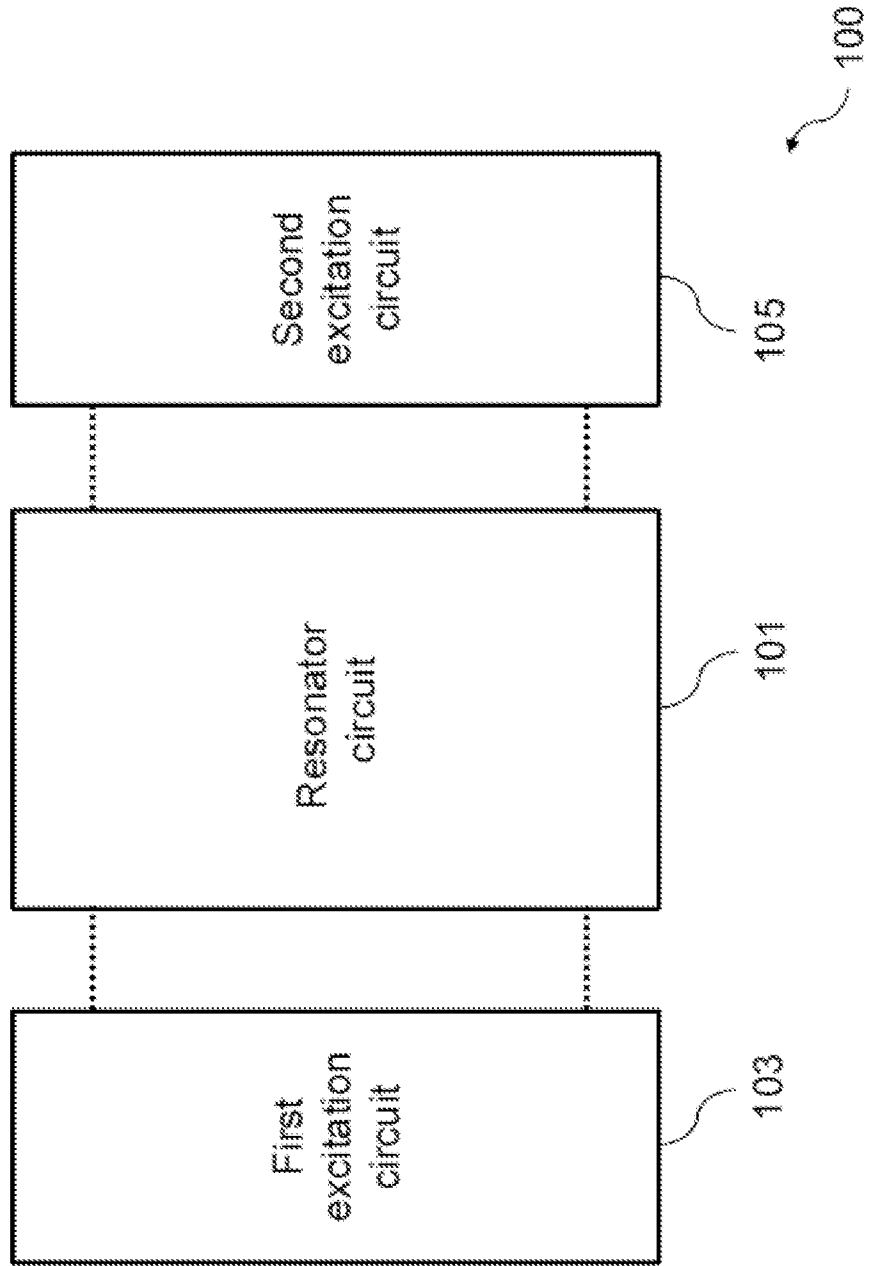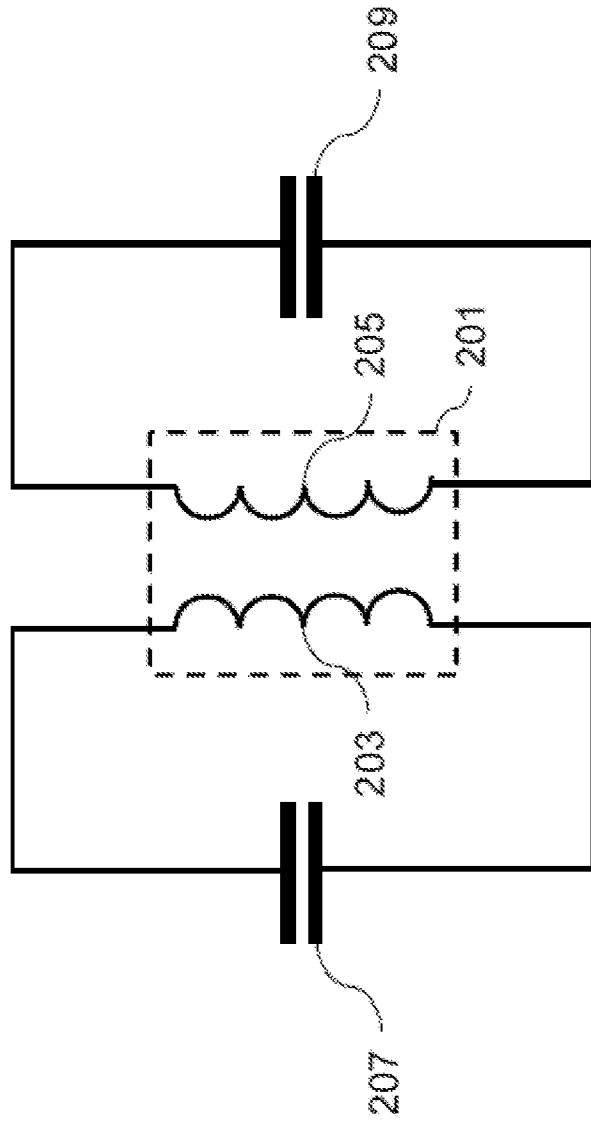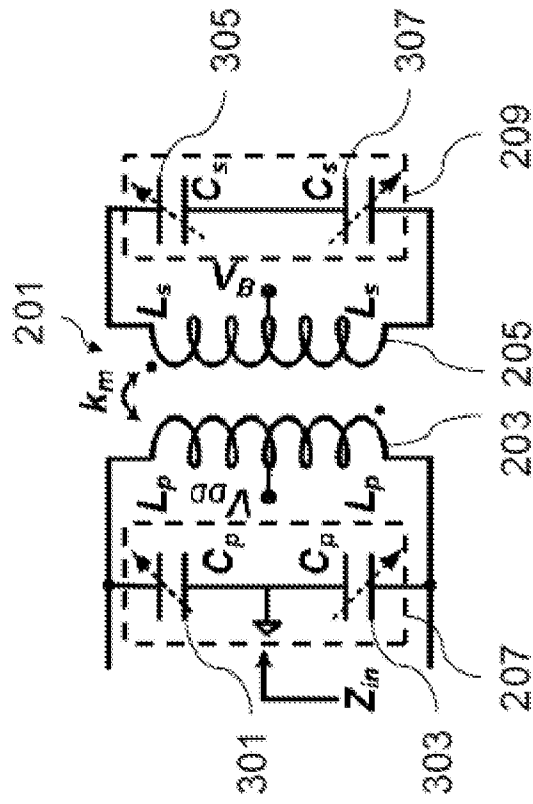EP/15701359.0-1206, Office Action, dated Jan. 2, 2020.

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Fig. 1

101

209

205

201

203

207

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

$$\omega_D \equiv \frac{1}{\sqrt{L_p(C_{p+}C_{eq}) + L_s C_s}}$$

$$\omega_C \equiv \frac{1}{\sqrt{L_p(C_p + C_{eq})}}$$
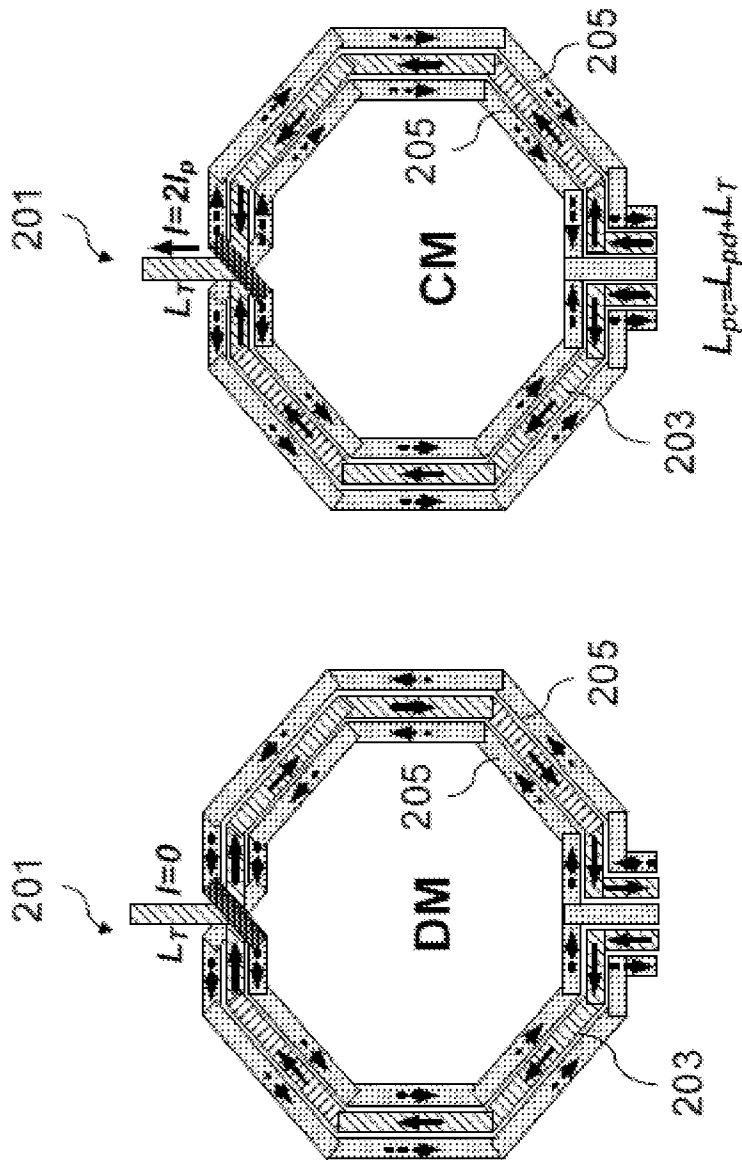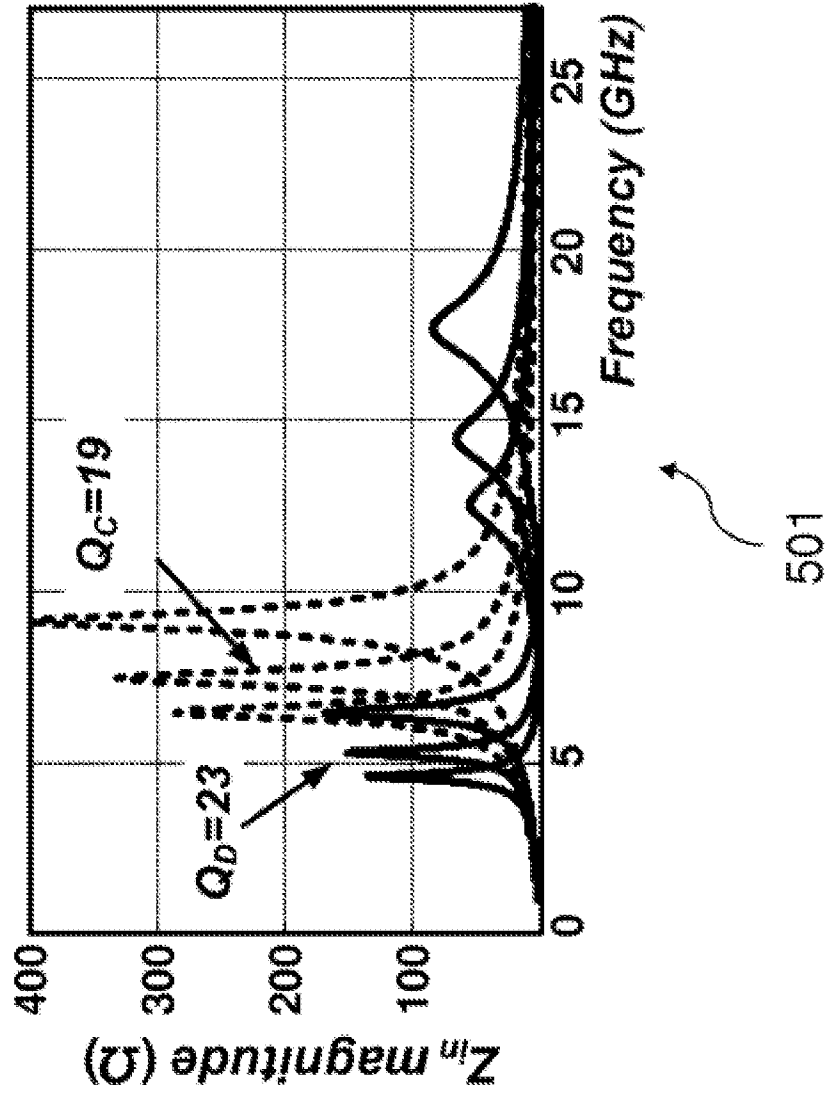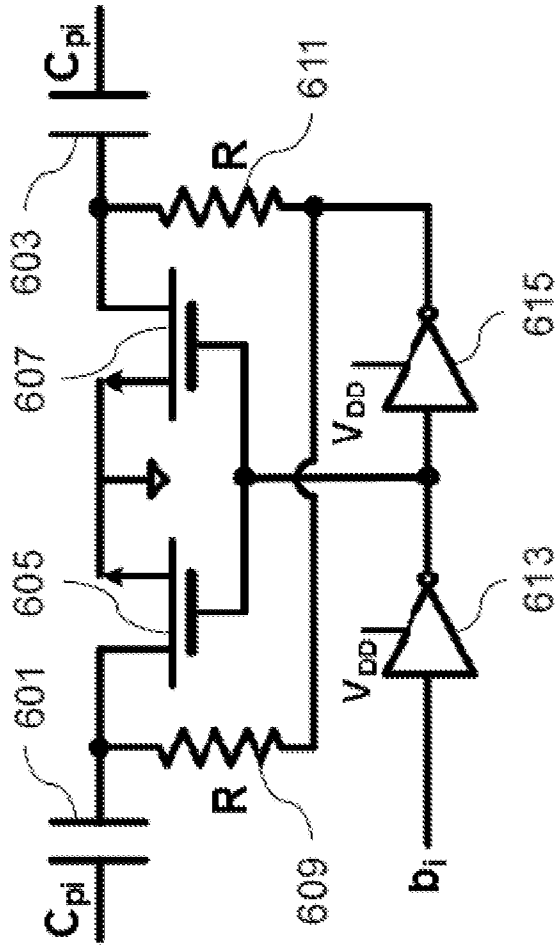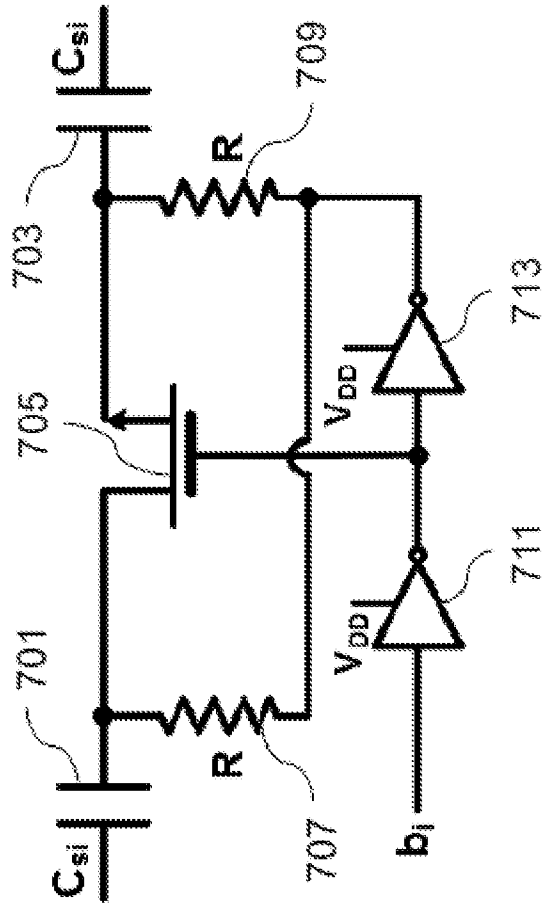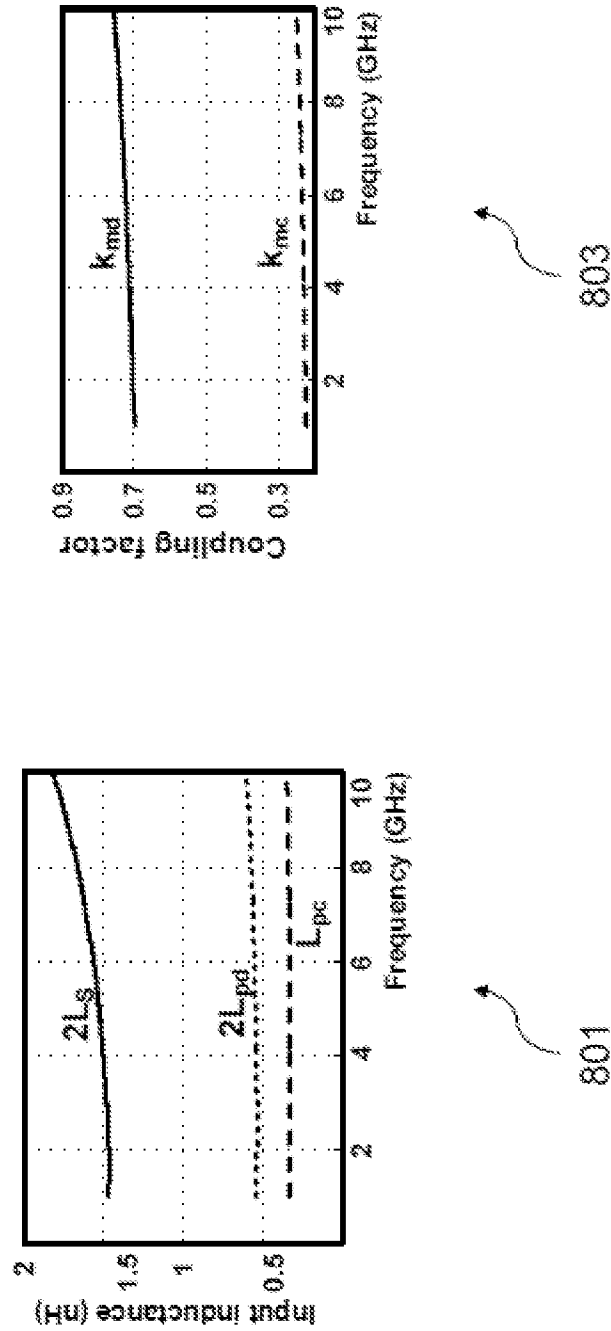
Fig. 9

Fig. 10

RADIO FREQUENCY OSCILLATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of International Application No. PCT/EP2015/051574, filed on Jan. 27, 2015, the disclosure of which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

The invention relates to the field of radio frequency (RF) oscillators.

BACKGROUND

Radio frequency oscillators are widely used in a variety of applications, such as for instance multi-mode multi-band applications. Radio freque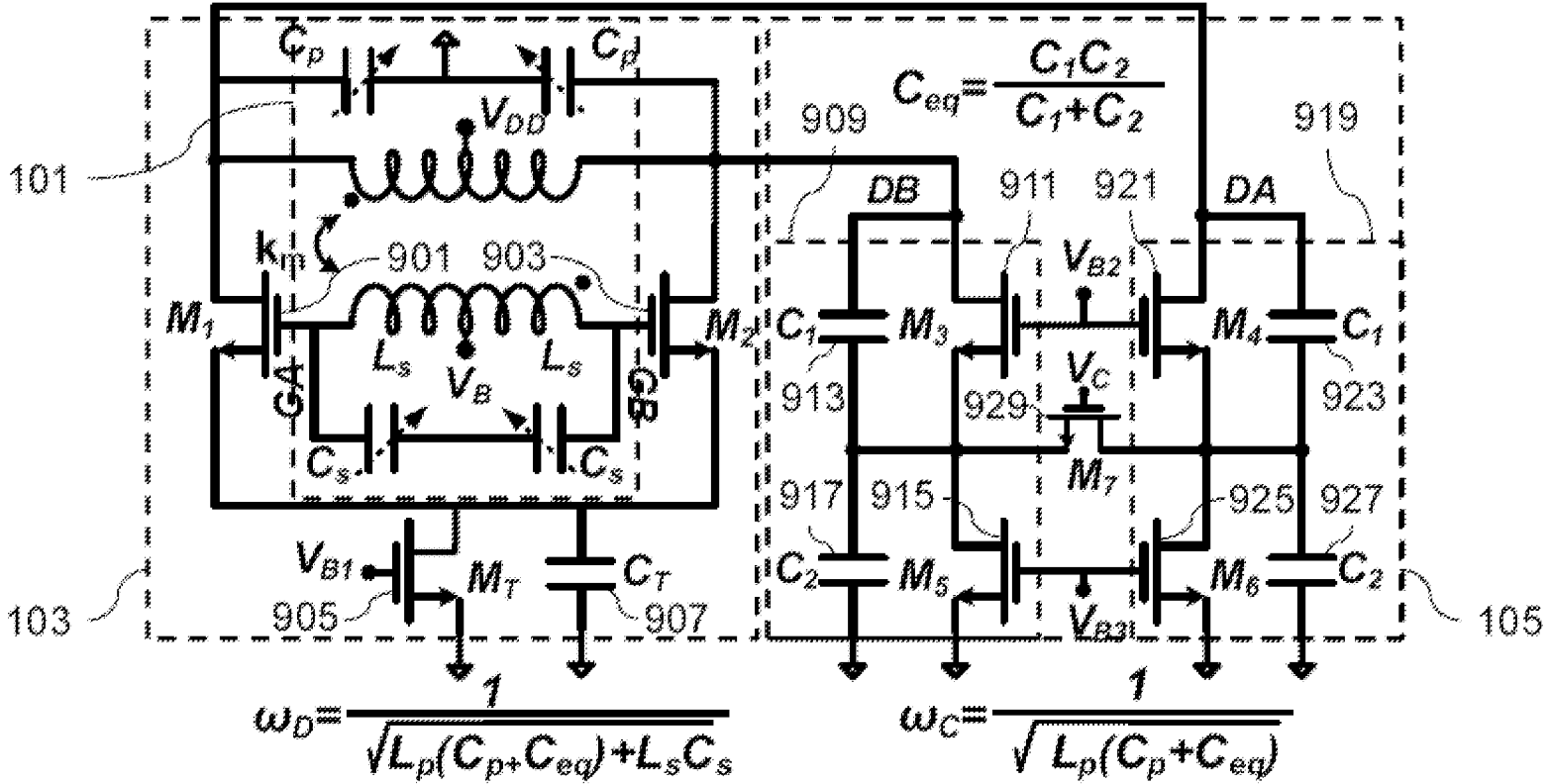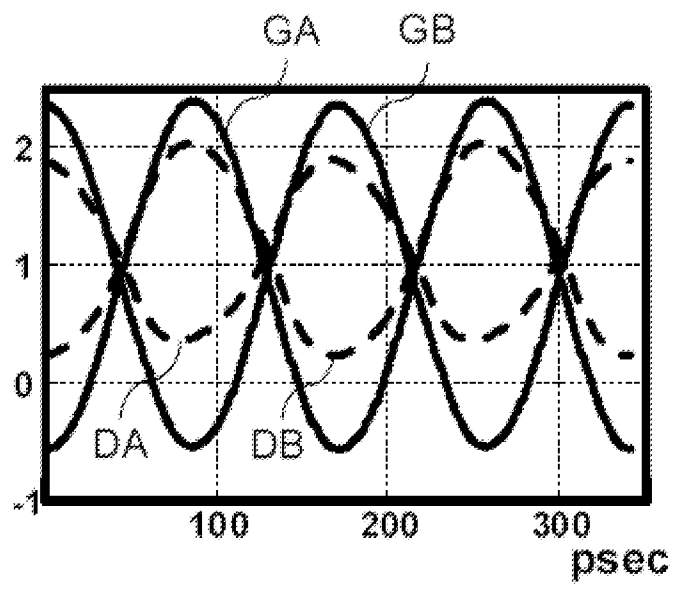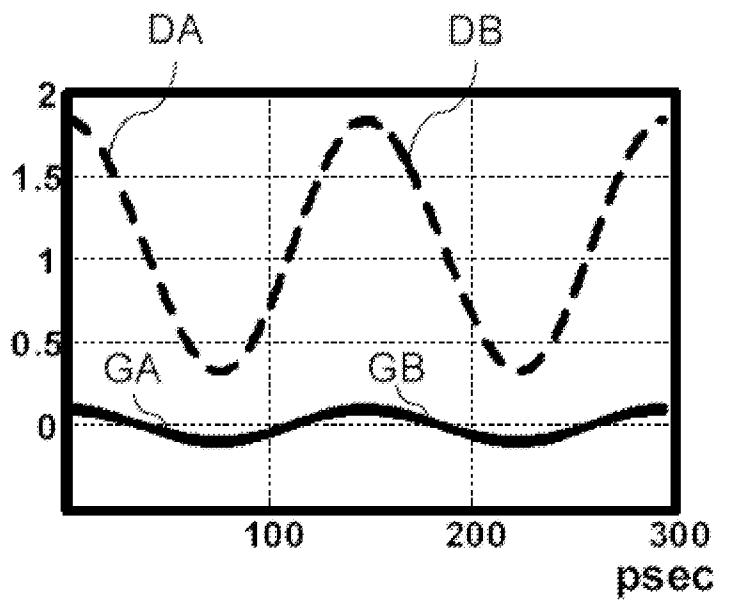ncy oscillators usually comprise resonator circuits as frequency selective elements, wherein the resonator circuits comprise inductors and capacitors. The inductors and capacitors are connected to be in resonance at a specific resonance frequency. For providing a high tuning range of a radio frequency oscillator, different approaches are applied.

An exemplary approach to provide an increased tuning range is to employ two separate radio frequency oscillators having separate resonator circuits and using high frequency multiplexers, which can lead to an increased power consumption and noise floor and can demand for a large die area. In L. Fanori et al., "A 2.4-to-5.3 GHz dual core CMOS VCO with concentric 8-shape coils," ISSCC Dig. Tech. Papers, pp 370-372, 17-21 Feb. 2013, a topology having separate resonator circuits is described.

A further exemplary approach is based on switching between even and odd resonance modes of a high-order LC resonator circuit within a radio frequency oscillator. A separation of resonance peaks in the different modes can be achieved, however, leading to a large size of the LC resonator circuit. In G. Li. et al., A Distributed dual-band LC oscillator based on Mode Switching," IEEE TMTT, vol. 59, no. 1, pp. 99-107, January 2011, a topology using mode switching is described.

Common radio frequency oscillators providing a high tuning range suffer from an increased noise floor and/or an increased size, in particular when implemented as radio frequency integrated circuits (RFICs) on semiconductor substrates.

SUMMARY

It is an object of the embodiments of the invention to provide an efficient radio frequency oscillator.

This object is achieved by the features of the independent claims. Further implementation forms are apparent from the dependent claims, the description and the figures.

The embodiments of the invention are based on the finding that a resonator circuit can be employed, wherein the resonator circuit is resonant at an excitation in a differential mode and at an excitation in a common mode. The resonator circuit can have different resonance frequencies when excited in the differential mode and the common mode, wherein the differential mode resonance frequency and the common mode resonance frequency can be tunable. This difference may be due to a different magnetic or inductive coupling factor, k_m, when the resonator circuit is excited in

the differential mode or the common mode. In particular, in the differential mode the coupling factor may be high, while in the common mode the coupling factor may be low.

The resonator circuit is excited by a first excitation circuit in the differential mode and by a second excitation circuit in the common mode. Therefore, a differential mode oscillator signal oscillating at the differential mode resonance frequency and a common mode oscillator signal oscillating at the common mode resonance frequency are provided. The resonator circuit and the first excitation circuit can be arranged to form a cross-coupled oscillator or a transformer-coupled oscillator. The resonator circuit and the second excitation circuit can be arranged to form a Colpitts oscillator. Consequently, the radio frequency oscillator employs a single resonator circuit or tank circuit. Furthermore, extra tuning range can be gained using the common mode oscillation without any area penalty or degradation of the differential mode oscillation performance.

Efficient structures of the radio frequency oscillator and the resonator circuit are provided, allowing for a high tuning range of the radio frequency oscillator while having a low size. The radio frequency oscillator and the resonator circuit can be compact. The resonator circuit and the radio frequency oscillator are suited for implementation as radio frequency integrated circuits (RFICs) on semiconductor substrates.

According to a first aspect, an embodiment of the invention relates to a radio frequency oscillator, the radio frequency oscillator comprising a resonator circuit being resonant at an excitation of the resonator circuit in a differential mode and at an excitation of the resonator circuit in a common mode, wherein the resonator circuit has a differential mode resonance frequency at the excitation in the differential mode, and wherein the resonator circuit has a common mode resonance frequency at the excitation in the common mode, a first excitation circuit being configured to excite the resonator circuit in the differential mode to obtain a differential mode oscillator signal oscillating at the differential mode resonance frequency, and a second excitation circuit being configured to excite the resonator circuit in the common mode to obtain a common mode oscillator signal oscillating at the common mode resonance frequency. Thus, an efficient radio frequency oscillator is provided.

The radio frequency oscillator can be a dual-mode radio frequency oscillator providing the differential mode oscillator signal and the common mode oscillator signal.

The resonator circuit can be a tank circuit. The resonator circuit can be used as a frequency selective element within the radio frequency oscillator. The resonator circuit can be resonant when excited in the differential mode and in the common mode.

In a first implementation form of the radio frequency oscillator according to the first aspect as such, the resonator circuit comprises a transformer, a primary capacitor, and a secondary capacitor, wherein the transformer comprises a primary winding and a secondary winding, the primary winding being inductively coupled with the secondary winding, wherein the primary capacitor is connected to the primary winding, the primary capacitor and the primary winding forming a primary circuit, and wherein the secondary capacitor is connected to the secondary winding, the secondary capacitor and the secondary winding forming a secondary circuit. Thus, an efficient resonator circuit is used within the radio frequency oscillator.

The differential mode resonance frequency can depend on the inductance of the primary winding, the inductance of the

secondary winding, the capacitance of the primary capacitor, and the capacitance of the secondary capacitor.

The common mode resonance frequency can depend on the inductance of the primary winding and the capacitance of the primary capacitor. The common mode resonance frequency may not depend on the inductance of the secondary winding and the capacitance of the secondary capacitor.

In a second implementation form of the radio frequency oscillator according to the first implementation form of the first aspect, the resonator circuit has the common mode resonance frequency at an excitation of the primary circuit in the common mode, and the resonator circuit has the differential mode resonance frequency at an excitation of the primary circuit in the differential mode. Thus, the differential mode oscillator signal and the common mode oscillator signal can be provided efficiently.

The primary winding and the secondary winding can be arranged to provide a strong inductive coupling when the primary circuit is excited in the differential mode and a weak inductive coupling when the primary circuit is excited in the common mode.

In a third implementation form of the radio frequency oscillator according to the first implementation form or the second implementation form of the first aspect, the primary winding of the transformer comprises one turn, and the secondary winding of the transformer comprises two turns. Thus, a resonator circuit with area efficiency is provided.

When the primary winding is excited in differential mode within a 1:2 transformer, induced currents at the secondary winding can have the same direction resulting in a strong coupling factor. A common mode excitation of the primary winding can induce currents at the secondary winding that circulate in opposite directions canceling each other resulting in a weak coupling factor.

A 2:1 transformer can have the same properties and can be used alternatively. 1:2 transformers and 2:1 transformers can be smallest size transformers having this property thus being area efficient. The primary capacitor can comprise a pair of single-ended capacitors for an efficient provision of a common mode oscillation.

In a fourth implementation form of the radio frequency oscillator according to the first implementation form to the third implementation form of the first aspect, the primary winding of the transformer and/or the secondary winding of the transformer is planar. Thus, a resonator circuit with area efficiency is provided.

In a fifth implementation form of the radio frequency oscillator according to the first implementation form to the fourth implementation form of the first aspect, the primary winding of the transformer and the secondary winding of the transformer are arranged on the same plane. Thus, a high coupling factor in differential mode and a low coupling factor in common mode is provided efficiently.

Different planes for the primary winding and the secondary winding can be used yielding a reduced size. In this case, the coupling factor in differential mode may be not as high as for the primary winding and the secondary winding of the transformer being arranged on the same plane. Furthermore, the winding being arranged at a lower metal plane can have a reduced quality factor Q and can yield a decreased phase noise performance. For the primary winding and the secondary winding being arranged on the same plane, a high coupling factor in differential mode and a low coupling factor in common mode is thus provided efficiently.

The primary winding of the transformer and/or the secondary winding of the transformer can comprise a bridging portion being arranged at a different plane.

In a sixth implementation form of the radio frequency oscillator according to the first implementation form to the fifth implementation form of the first aspect, the primary winding of the transformer and/or the secondary winding of the transformer is connected to a constant voltage source or a ground potential. Thus, a tapping of the primary winding and/or the secondary winding is realized. Both the primary winding and the secondary winding may be connected to a constant voltage source respectively in order to enable an efficient start-up of the radio frequency oscillator.

The tapping of the primary winding and/or the secondary winding can be a symmetrical center tapping of the primary winding and/or the secondary winding. The center tapping at the primary winding can reduce the common mode resonance frequency and can increase an overlap between differential mode and common mode oscillation frequencies. This may not influence the tuning range of the radio frequency oscillator.

In a seventh implementation form of the radio frequency oscillator according to the first implementation form to the sixth implementation form of the first aspect, the primary capacitor of the primary circuit comprises a pair of single-ended capacitors. Thus, a reference to ground potential of the primary circuit is realized.

In an eighth implementation form of the radio frequency oscillator according to the first implementation form to the seventh implementation form of the first aspect, the secondary capacitor of the secondary circuit comprises a pair of differential capacitors. Thus, a reference to ground potential of the secondary circuit is avoided minimizing the effect of the secondary winding in common mode excitations. The pair of differential capacitors can be a pair of balanced capacitors.

In a ninth implementation form of the radio frequency oscillator according to the first implementation form to the eighth implementation form of the first aspect, the primary capacitor and/or the secondary capacitor comprises a variable capacitor, in particular a digitally tunable capacitor. Thus, a variation of the differential mode resonance frequency and/or the common mode resonance frequency can be realized efficiently.

In a tenth implementation form of the radio frequency oscillator according to the first implementation form to the ninth implementation form of the first aspect, the primary capacitor is connected in parallel to the primary winding, and/or the secondary capacitor is connected in parallel to the secondary winding. Thus, the primary circuit and the secondary circuit are realized as parallel circuits.

In an eleventh implementation form of the radio frequency oscillator according to the first aspect as such or any preceding implementation form of the first aspect, the first excitation circuit and/or the second excitation circuit comprises at least one transistor, in particular at least one field-effect transistor, for exciting the resonator circuit. Thus, an active device is employed for exciting the resonator circuit. The transistor can be a trans-conductance gm transistor. In order to realize a cross-coupled structure at least two transistors may be employed. The transistors can be metal-oxide-semiconductor field-effect transistors (MOSFETs).

In a twelfth implementation form of the radio frequency oscillator according to the first aspect as such or any preceding implementation form of the first aspect, the first excitation circuit comprises a transistor for controlling, in particular for activating and deactivating, the excitation of the resonator circuit in the differential mode, and/or the second excitation circuit comprises a transistor for control-

ling, in particular for activating and deactivating, the excitation of the resonator circuit in the common mode. Thus, the excitation of the resonator circuit in the differential mode and/or in the common mode can be controlled efficiently.

In a thirteenth implementation form of the radio frequency oscillator according to the first aspect as such or any preceding implementation form of the first aspect, the resonator circuit and the first excitation circuit are arranged to form a cross-coupled oscillator or a transformer-coupled oscillator to obtain the differential mode oscillator signal. Thus, an efficient excitation in differential mode is realized.

In a fourteenth implementation form of the radio frequency oscillator according to the first aspect as such or any preceding implementation form of the first aspect, the resonator circuit and the second excitation circuit are arranged to form a Colpitts oscillator to obtain the common mode oscillator signal. Thus, an efficient excitation in common mode is realized.

In a fifteenth implementation form of the radio frequency oscillator according to the fourteenth implementation form of the first aspect, the Colpitts oscillator comprises a first auxiliary oscillator and a second auxiliary oscillator, the first auxiliary oscillator being synchronizable with regard to the second auxiliary oscillator in frequency and phase. Thus, an injection locking between the first auxiliary oscillator and the second auxiliary oscillator is realized.

The two auxiliary oscillators comprised by the Colpitts oscillator can be locked together via a switch realized by a transistor, e.g. a MOS transistor. This switch can be off and can disconnect the outputs of the two auxiliary oscillators when the oscillator works in differential mode excitation. A differential mode oscillation can e.g. be provided when the Colpitts oscillator is off and the transformer-coupled oscillator is on.

In a sixteenth implementation form of the radio frequency oscillator according to the fourteenth implementation form or the fifteenth implementation form of the first aspect, the Colpitts oscillator is a single-ended oscillator. Thus, a reference to ground potential is realized.

According to a second aspect, an embodiment of the invention relates to a method for providing a differential mode oscillator signal and a common mode oscillator signal using a radio frequency oscillator, the radio frequency oscillator comprising a resonator circuit, a first excitation circuit, and a second excitation circuit, the resonator circuit being resonant at an excitation of the resonator circuit in a differential mode and at an excitation of the resonator circuit in a common mode, wherein the resonator circuit has a differential mode resonance frequency at the excitation in the differential mode, and wherein the resonator circuit has a common mode resonance frequency at the excitation in the common mode, the method comprising exciting, by the first excitation circuit, the resonator circuit in the differential mode to obtain the differential mode oscillator signal oscillating at the differential mode resonance frequency, and exciting, by the second excitation circuit, the resonator circuit in the common mode to obtain the common mode oscillator signal oscillating at the common mode resonance frequency. Thus, the differential mode oscillator signal and the common mode oscillator signal are provided efficiently.

The method can be performed by the radio frequency oscillator. Further features of the method directly result from the functionality of the radio frequency oscillator.

The embodiments of the invention can be implemented using hardware and/or software.

SHORT DESCRIPTION OF EMBODIMENTS

Embodiments of the invention will be described with respect to the following figures, in which:

FIG. 1 shows a diagram of a radio frequency oscillator according to an embodiment;

FIG. 2 shows a diagram of a resonator circuit according to an embodiment;

FIG. 3 shows a diagram of a resonator circuit according to an embodiment;

FIG. 4 shows a diagram of a transformer of a resonator circuit according to an embodiment;

FIG. 5 shows a diagram of an input impedance response of a resonator circuit according to an embodiment;

FIG. 6 shows a diagram of a single-ended capacitor according to an embodiment;

FIG. 7 shows a diagram of a differential capacitor according to an embodiment;

FIG. 8 shows a diagram of an input inductance response and a coupling factor response according to an embodiment;

FIG. 9 shows a diagram of a radio frequency oscillator according to an embodiment; and

FIG. 10 shows a diagram of differential mode oscillator signals and common mode oscillator signals according to an embodiment.

DETAILED DESCRIPTION OF EMBODIMENTS

The design of radio frequency oscillators for multi-mode multi-band cellular applications can demand for a high tuning range (TR) while ensuring low phase noise (PN) for a wide range of frequency bands and channels. Low quality factors Q of resonator circuits, e.g. comprising switched-capacitor networks for wide tuning ranges, can limit the phase noise performance of radio frequency oscillators.

Embodiments of the invention are based on an increased tuning range of a radio frequency oscillator having a single resonator circuit by introducing a common mode oscillation. The common mode oscillation increases the tuning range of the radio frequency oscillator without any die area and/or phase noise penalty. The radio frequency oscillator can be regarded as a dual-mode radio frequency oscillator having a single resonator circuit. The resonator circuit can also be referred to as a tank circuit.

FIG. 1 shows a diagram of a radio frequency oscillator 100 according to an embodiment. The radio frequency oscillator 100 comprises a resonator circuit 101 being resonant at an excitation of the resonator circuit 101 in a differential mode and at an excitation of the resonator circuit 101 in a common mode, wherein the resonator circuit 101 has a differential mode resonance frequency at the excitation in the differential mode, and wherein the resonator circuit 101 has a common mode resonance frequency at the excitation in the common mode, a first excitation circuit 103 being configured to excite the resonator circuit 101 in the differential mode to obtain a differential mode oscillator signal oscillating at the differential mode resonance frequency, and a second excitation circuit 105 being configured to excite the resonator circuit 101 in the common mode to obtain a common mode oscillator signal oscillating at the common mode resonance frequency.

In an embodiment, the resonator circuit 101 comprises a transformer, a primary capacitor, and a secondary capacitor, wherein the transformer comprises a primary winding and a secondary winding, the primary winding being inductively coupled with the secondary winding, wherein the primary capacitor is connected to the primary winding, the primary capacitor and the primary winding forming a primary circuit, and wherein the secondary capacitor is connected to the secondary winding, the secondary capacitor and the secondary winding forming a secondary circuit.

FIG. 2 shows a diagram of a resonator circuit 101 according to an embodiment. The resonator circuit 101 is resonant at an excitation of the resonator circuit 101 in a differential mode and at an excitation of the resonator circuit 101 in a common mode, wherein the resonator circuit 101 has a differential mode resonance frequency at the excitation in the differential mode, and wherein the resonator circuit 101 has a common mode resonance frequency at the excitation in the common mode.

The resonator circuit 101 comprises a transformer 201, a primary capacitor 207, and a secondary capacitor 209, wherein the transformer 201 comprises a primary winding 203 and a secondary winding 205, the primary winding 203 being inductively coupled with the secondary winding 205, wherein the primary capacitor 207 is connected to the primary winding 203, the primary capacitor 207 and the primary winding 203 forming a primary circuit, and wherein the secondary capacitor 209 is connected to the secondary winding 205, the secondary capacitor 209 and the secondary winding 205 forming a secondary circuit.

The resonator circuit 101 has the common mode resonance frequency at an excitation of the primary circuit in the common mode. The resonator circuit 101 has the differential mode resonance frequency at an excitation of the primary circuit in the differential mode.

In the following, further implementation forms and embodiments of the radio frequency oscillator 100 are described.

FIG. 3 shows a diagram of a resonator circuit 101 according to an embodiment. The resonator circuit 101 comprises a transformer 201, a primary capacitor 207, and a secondary capacitor 209, wherein the transformer 201 comprises a primary winding 203 and a secondary winding 205, the primary winding 203 being inductively coupled with the secondary winding 205, wherein the primary capacitor 207 is connected to the primary winding 203, the primary capacitor 207 and the primary winding 203 forming a primary circuit, and wherein the secondary capacitor 209 is connected to the secondary winding 205, the secondary capacitor 209 and the secondary winding 205 forming a secondary circuit.

The primary capacitor 207 of the primary circuit comprises a pair of single-ended capacitors 301, 303. The secondary capacitor 209 of the secondary circuit comprises a pair of differential capacitors 305, 307. k_m denotes the magnetic or inductive coupling factor between the primary winding 203 and the secondary winding 205, wherein $0 \leq |k_m| \leq 1$.

The inductance of the primary winding 203 can be referred to as L_p, the inductance of the secondary winding 205 can be referred to as L_s, the capacitance of the primary capacitor 207 can be referred to as C_p, and the capacitance of the secondary capacitor 209 can be referred to as C_s. According to this definition, the primary winding 203, the secondary winding 205, the primary capacitor 207, and the secondary capacitor 209 are considered as individual concentrated components.

Alternatively, the inductance of the primary winding 203 can be referred to as $2 L_p$, the inductance of the secondary winding 205 can be referred to as $2 L_s$, the capacitance of the primary capacitor 207 can be referred to as $0.5 C_p$, and the capacitance of the secondary capacitor 209 can be referred to as $0.5 C_s$. According to this definition, the primary winding 203 and the secondary winding 205 are each formed by a pair of inductors connected in series, wherein the inductance of each inductor is referred to as L_p or L_s, respectively. Furthermore, the primary capacitor 207 and the

secondary capacitor 209 are each formed by a pair of capacitors connected in series, wherein the capacitance of each capacitor is referred to as C_p or C_s, respectively.

FIG. 4 shows a diagram of a transformer 201 of a resonator circuit 101 according to an embodiment. The transformer 201 comprises a primary winding 203 and a secondary winding 205, the primary winding 203 being inductively coupled with the secondary winding 205. The primary winding 203 comprises one turn and the secondary winding 205 comprises two turns, realizing a ratio of turns of 1:2. The diagram illustrates induced currents within the transformer 201 at an excitation in differential mode (DM) and an excitation in common mode (CM).

Embodiments of the invention are based on different resonance frequencies of the transformer-based resonator circuit 101 at differential mode excitations and common mode excitations. The different resonance frequencies can be due to a different inductive coupling factor k_m when the primary winding 203 of the transformer 201 is excited by differential mode or common mode signals.

The induced currents at the secondary winding 205 at differential mode excitation can circulate in same directions and can provide a high coupling factor k_m between the primary winding 203 and the secondary winding 205 of the transformer 201. Consequently, in differential mode, the inductance of the secondary winding 205 and the capacitance of the secondary capacitor 209 can strongly affect the differential mode characteristics of the resonator circuit 101, e.g. the differential mode resonance frequency. For a coupling factor in differential mode $k_{n,DM} > 0.5$, the differential mode resonance frequency can be at $\omega_{0,DM} = 1/\mathrm{sqrt}(L_p C_p + L_s C_s)$.

On the other hand, the induced currents at the secondary winding 205 at common mode excitation can circulate in opposite directions and can cancel each other. Hence, the coupling factor k_m can be low in the common mode, e.g. $k_{m,CM} < 0.3$. This low coupling factor k_m can be interpreted as the secondary winding 205 not being seen from the primary winding 203. Thus, the common mode resonance frequency can be at $\omega_{0,CM} = 1/\mathrm{sqrt}(L_p C_p)$. Since common mode excitation signals at the primary circuit may not see the secondary circuit, in particular the differential capacitors 305, 307, the primary capacitor 207 can comprise single-ended capacitors 301, 303. The common mode resonance frequency $\omega_{0,CM}$ can be higher than the differential mode resonance frequency $\omega_{0,DM}$ and the frequency separation can be controlled by the ratio $L_s C_s / L_p C_p$.

The differential mode resonance frequency can be determined as $\omega_{0,DM} = 1/\mathrm{sqrt}(L_p C_p + L_s C_s)$. Further differential mode resonance frequencies can be determined as $\omega_{n,DM} = n \, \omega_{0,DM}$, wherein n can be any number, and wherein n can depend on an inductive coupling factor between the primary winding 203 and the secondary winding 205, and the ratio $(L_s C_s)/(L_p C_p)$.

The inductance associated with the primary winding 203 in common mode L_{pc} can be different from the inductance associated with the primary winding 203 in differential mode L_{pd}. It can be considered in the design phase that $L_{pc} > L_{pd}$. The ratio of capacitances of the primary capacitor 207 and the secondary capacitor 209 can be designed based on a value of L_{pc}, e.g. $L_{pc} = L_{pd} + L_T$, wherein L_T denotes an inductance of a metal track connecting the center tap of the primary winding 203 e.g. to a constant voltage source.

FIG. 5 shows a diagram of an input impedance response 501 of a resonator circuit 101 according to an embodiment. The diagram illustrates differential mode resonance frequencies and common mode resonance frequencies.

The input impedance of the resonator circuit **101** is denoted as Z_{in}. The quality factor in common mode Q_C can be slightly less than the quality factor in differential mode Q_D but may be large enough such that oscillation is possible in this mode. If the quality factor of a resonator circuit is large, an oscillation start-up can easier be realized. In the diagram, Q_C is smaller than Q_D but is still large enough for an efficient oscillation start-up.

Assuming a maximum to minimum capacitance ratio $C_{max}/C_{min}=2$ for the primary capacitor **207** or the secondary capacitor **209**, which can be variable or switchable capacitors, enabling a sufficiently high quality factor of the capacitors, both the differential mode resonance frequency and the common mode resonance frequency can vary, e.g. by 34%.

In order to avoid any gaps between the tuning ranges in differential mode and in common mode, there can be some overlap. This can mean that at least the lowest common mode resonance frequency $\omega_{CM,low}$ equals the highest differential mode resonance frequency $\omega_{DM,high}$, i.e. $\omega_{CM,low}=\omega_{DM,high}$. Satisfying the overlap relationship can result in $L_sC_s=L_pC_p$.

With these relationships, the resonance frequencies can cover an octave while going from differential mode oscillations to common mode oscillations. Practically, the ratio C_{max}/C_{min} may be greater than 2, due to parasitic effects and challenges associated with controlling the precise overlap between the differential mode resonance frequencies and the common mode resonance frequencies.

In an embodiment, an octave tuning range for the radio frequency oscillator is achieved upon the basis of the following equations:

$$\frac{C_{max,p}}{C_{min,p}} = 2 \quad \frac{C_{max,s}}{C_{min,s}} = 2$$

$$C_{max,p} = C_p, \quad C_{max,s} = C_s$$

$$\left. \begin{array}{l} \omega_D: \dfrac{1}{\sqrt{L_pC_p + L_sC_s}} \sim \dfrac{\sqrt{2}}{\sqrt{L_pC_p + L_sC_s}} \\ \\ \omega_C: \dfrac{1}{\sqrt{L_pC_p}} \sim \dfrac{\sqrt{2}}{\sqrt{L_pC_p}} \end{array} \right\} \xrightarrow[\text{overlap}]{\text{for}} L_pC_p = L_sC_s$$

wherein $C_{max,p}/C_{min,p}$ denotes a maximum to minimum capacitance ratio associated with the primary capacitor **207**, $C_{max,s}/C_{min,s}$ denotes a maximum to minimum capacitance ratio associated with the secondary capacitor **209**, ω_D relates to the differential mode resonance frequencies, and ω_D relates to the common mode resonance frequencies.

FIG. **6** shows a diagram of a single-ended capacitor **301**, **303** according to an embodiment. The single-ended capacitor **301**, **303** comprises a capacitor **601**, a capacitor **603**, a transistor **605**, a transistor **607**, a resistor **609**, a resistor **611**, an inverter **613**, and an inverter **615**. The single-ended capacitor **301**, **303** is arranged within the primary circuit of the resonator circuit **101**.

By applying a digital switching signal b_i, the transistor **605** and the transistor **607** can be switched between a conducting state and a non-conducting state. Consequently, the capacitance of the single-ended capacitor **301**, **303** can be digitally tuned. A plurality of single-ended capacitors **301**, **303** can be connected in parallel.

FIG. **7** shows a diagram of a differential capacitor **305**, **307** according to an embodiment. The differential capacitor **305**, **307** comprises a capacitor **701**, a capacitor **703**, a

transistor **705**, a resistor **707**, a resistor **709**, an inverter **711**, and an inverter **713**. The differential capacitor **305**, **307** is arranged within the secondary circuit of the resonator circuit **101**.

By applying a digital switching signal the transistor **705** can be switched between a conducting state and a non-conducting state. Consequently, the capacitance of the differential capacitor **305**, **307** can be digitally tuned. A plurality of differential capacitors **305**, **307** can be connected in parallel.

FIG. **8** shows a diagram of an input inductance response **801** and a coupling factor response **803** according to an embodiment.

The input inductance **801** relates to the inductances of the primary winding **203** and the secondary winding **205** of the transformer **201**. The inductance 2 L_s is approximately 1.5 nH. The inductance 2 L_{pd} is approximately 0.5 nH. The inductance L_{pc} is approximately 0.4 nH. The inductances slightly increase with frequency.

The coupling factor response **803** relates to coupling factors of the transformer **201** at an excitation in differential mode and in common mode. The coupling factor in differential mode k_{md} is approximately 0.7. The coupling factor in common mode k_{mc} is approximately 0.25. The coupling factors slightly increase with frequency.

FIG. **9** shows a diagram of a radio frequency oscillator **100** according to an embodiment. The radio frequency oscillator **100** comprises a resonator circuit **101** being resonant at an excitation of the resonator circuit **101** in a differential mode and at an excitation of the resonator circuit **101** in a common mode, wherein the resonator circuit **101** has a differential mode resonance frequency at the excitation in the differential mode, and wherein the resonator circuit **101** has a common mode resonance frequency at the excitation in the common mode, a first excitation circuit **103** being configured to excite the resonator circuit **101** in the differential mode to obtain a differential mode oscillator signal oscillating at the differential mode resonance frequency, and a second excitation circuit **105** being configured to excite the resonator circuit **101** in the common mode to obtain a common mode oscillator signal oscillating at the common mode resonance frequency.

The resonator circuit **101** forms an implementation of the resonator circuit **101** as described in conjunction with FIG. **3**. The first excitation circuit **103** comprises a transistor **901**, a transistor **903**, a tail transistor **905**, and a tail capacitor **907**. The second excitation circuit **105** comprises a first auxiliary oscillator **909**, the first auxiliary oscillator **909** comprising a transistor **911**, a capacitor **913**, a transistor **915**, and a capacitor **917**. The second excitation circuit **105** further comprises a second auxiliary oscillator **919**, the second auxiliary oscillator **919** comprising a transistor **921**, a capacitor **923**, a transistor **925**, and a capacitor **927**.

The resonator circuit **101** and the first excitation circuit **103** are arranged to form a transformer-coupled oscillator to obtain the differential mode oscillator signal. The resonator circuit **101** and the second excitation circuit **105** are arranged to form a Colpitts oscillator to obtain the common mode oscillator signal.

The first auxiliary oscillator **909** and the second auxiliary oscillator **919** are connected by a transistor **929**. The first auxiliary oscillator **909** is synchronizable with regard to the second auxiliary oscillator **919** in frequency and phase via the transistor **929**. The first auxiliary oscillator **909** can be injection-locked on the second auxiliary oscillator **919**.

Exciting the resonator circuit **101**, in particular the transformer **201** of FIG. **2**, in the differential mode to obtain the

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differential mode oscillator signal oscillating at the differential mode resonance frequency can be achieved e.g. by using a cross-coupled gm-pair structure or a transformer-coupled structure within the first excitation circuit **103**. A separate second excitation circuit **105** may be used in order to excite the resonator circuit **101** in the common mode. Thus, a dual mode oscillation in terms of a differential mode oscillation and a common mode oscillation can be provided.

The described structure is depicted in FIG. **9**. The first excitation circuit **103** of the radio frequency oscillator **100** is structured according to a transformer-coupled structure for obtaining the differential mode oscillation in conjunction with the resonator circuit **101**. The second excitation circuit **105** of the radio frequency oscillator **100** is structured as a Colpitts oscillator in conjunction with the resonator circuit **101**. The Colpitts oscillator is single-ended. The Colpitts oscillator comprises two auxiliary oscillators **909**, **919**, in particular two cores, with the auxiliary oscillators **909**, **919** being injection-locked through the transistor **929** or M7 switch. Both auxiliary oscillators **909**, **919** can start oscillating at the same frequency but slightly out of phase. Later, the auxiliary oscillators **909**, **919** can lock and there may be no phase shift between them. Therefore, the resonator circuit **101**, in particular the transformer, is excited in the common mode to obtain the common mode oscillator signal oscillating at the common mode resonance frequency. The injection-locking of the two auxiliary oscillators **909**, **919** can lead to a 3 dB improvement in phase noise performance. The radio frequency oscillator **100** can exhibit a phase noise characteristic having two distinctive regions.

When exciting in differential mode, the voltages V_{B2} and V_{B3} can be zero, i.e. $V_{B2}=V_{B3}=0$, and the transistor **929** can be switched off for providing an efficient excitation in differential mode. When exciting in common mode, the voltage V_{B1} can be zero, i.e. $V_{B1}=0$, and the transistor **929** can be switched on.

The differential mode resonance frequency ω_D and the common mode resonance frequency ω_C can be determined according to the following equations:

$$\omega_D = \frac{1}{\sqrt{L_p(C_p + C_{eq}) + L_s C_s}}$$

$$\omega_C = \frac{1}{\sqrt{L_p(C_p + C_{eq})}}$$

$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

wherein C_{eq} denotes an equivalent capacitance determined upon the basis of the capacitances of the capacitors **913**, **917**, **923**, **927**.

In order to relax the start-up conditions e.g. of the Colpitts oscillator, C_{eq} can be designed to be larger than C_p through the tuning range. This may reduce the tuning range of both the differential mode and common mode oscillations. The reduced tuning range can be more visible in common mode since in differential mode the primary and secondary capacitors can both affect the resonance frequency. By choosing $L_s C_s > L_p C_p$, this effect can be reduced even more in differential mode, without changing the common mode conditions.

FIG. **10** shows a diagram of differential mode oscillator signals **1001** and common mode oscillator signals **1003** according to an embodiment. The differential mode oscilla-

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tor signals **1001** and the common mode oscillator signals **1003** are depicted for probe positions GA, GB, DA, and DB as shown in FIG. **9**. The differential mode oscillator signals **1001** and the common mode oscillator signals **1003** are sinusoidal signals over time.

Embodiments of the invention use different characteristics of a 1:2 transformer **201** in differential mode excitation and in common mode excitation, and use an additional common mode oscillator signal to a differential mode oscillator signal, using the same resonator circuit **101** and hence imply no die area penalty. Furthermore, since differential mode and common mode start-up circuits can share the same output, there may be no need for multiplexing and hence no noise floor degradation.

What is claimed is:

1. A radio frequency oscillator, comprising:
   a resonator circuit:
   resonant and having a differential mode resonance frequency at an excitation of the resonator circuit in a differential mode, and
   resonant and having a common mode resonance frequency at an excitation of the resonator circuit in a common mode;
   a first excitation circuit configured to excite the resonator circuit in the differential mode to obtain a differential mode oscillator signal oscillating at the differential mode resonance frequency; and
   a second excitation circuit configured to excite the resonator circuit in the common mode to obtain a common mode oscillator signal oscillating at the common mode resonance frequency,
   wherein the resonator circuit and the second excitation circuit are arranged to form a Colpitts oscillator to obtain the common mode oscillator signal and the Colpitts oscillator is a single-ended oscillator.

2. The radio frequency oscillator of claim **1**, wherein the resonator circuit comprises:
   a transformer comprising a primary winding inductively coupled with a secondary winding,
   a primary capacitor connected to the primary winding, and
   a secondary capacitor connected to the secondary winding,
   wherein the primary capacitor and the primary winding form a primary circuit, and the secondary capacitor and the secondary winding form a secondary circuit.

3. The radio frequency oscillator of claim **2**, wherein the resonator circuit has the common mode resonance frequency at an excitation of the primary circuit in the common mode, and the resonator circuit has the differential mode resonance frequency at an excitation of the primary circuit in the differential mode.

4. The radio frequency oscillator of claim **2**, wherein the primary winding of the transformer comprises one turn, and the secondary winding of the transformer comprises two turns.

5. The radio frequency oscillator of claim **2**, wherein at least one of the primary winding of the transformer and the secondary winding of the transformer is planar.

6. The radio frequency oscillator of claim **2**, wherein the primary winding of the transformer and the secondary winding of the transformer are arranged on the same plane.

7. The radio frequency oscillator of claim **2**, wherein at least one of the primary winding of the transformer and the secondary winding of the transformer is connected to a constant voltage source.

8. The radio frequency oscillator of claim **2**, wherein the primary capacitor of the primary circuit comprises a pair of single-ended capacitors.

9. The radio frequency oscillator of claim **2**, wherein the secondary capacitor of the secondary circuit comprises a pair of differential capacitors.

10. The radio frequency oscillator of claim **2**, wherein at least one of the primary capacitor and the secondary capacitor comprises a variable capacitor.

11. The radio frequency oscillator of claim **1**, wherein at least one of the first excitation circuit and the second excitation circuit comprises at least one transistor, for exciting the resonator circuit.

12. The radio frequency oscillator of claim **1**, wherein the resonator circuit and the first excitation circuit are arranged to form a cross-coupled oscillator to obtain the differential mode oscillator signal.

13. The radio frequency oscillator of claim **1**, wherein the Colpitts oscillator comprises a first auxiliary oscillator and a second auxiliary oscillator, the first auxiliary oscillator being synchronizable with regard to the second auxiliary oscillator in frequency and phase.

14. The radio frequency oscillator of claim **2**, wherein at least one of the primary winding of the transformer and the secondary winding of the transformer is connected to a ground potential.

15. The radio frequency oscillator of claim **10**, wherein the variable capacitor is a digitally tunable capacitor.

16. The radio frequency oscillator of claim **11**, wherein the at least one transistor is a field-effect transistor.

17. The radio frequency oscillator of claim **1**, wherein the resonator circuit and the first excitation circuit are arranged to form a transformer-coupled oscillator to obtain the differential mode oscillator signal.

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