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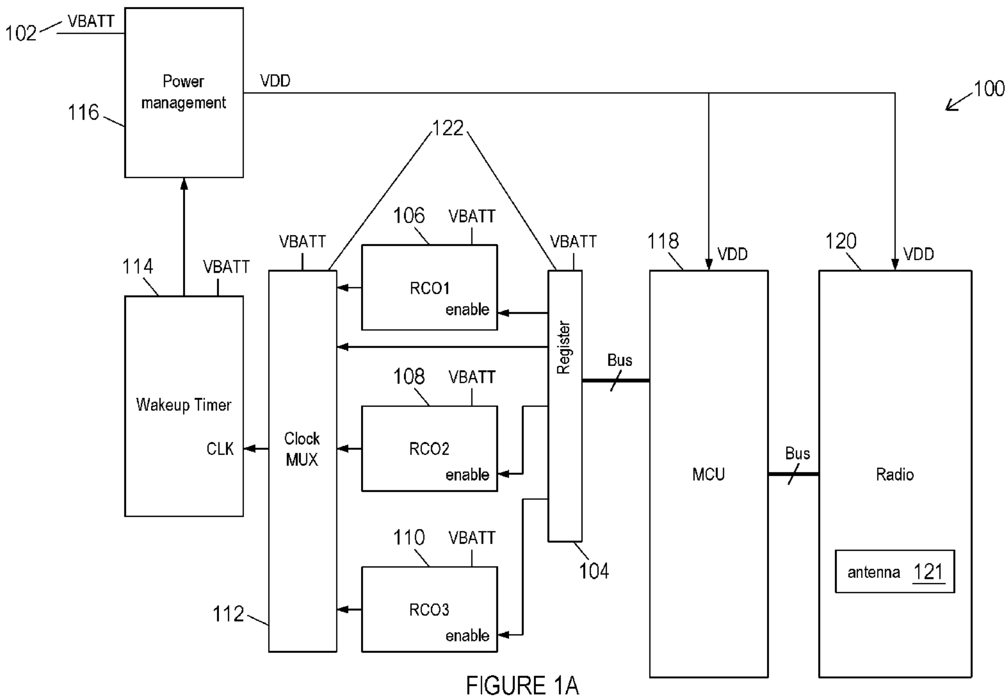

FIGURE 1A

(57) Abstract: An device having an oscillator circuit modifiable between a first operating mode and a second operating mode, wherein the first operating mode has a first frequency accuracy and a first power consumption, wherein the second operating mode has a second frequency accuracy and a second power consumption, wherein the second frequency accuracy is more accurate than the first frequency accuracy and the second power consumption is higher than the first power consumption, and a control circuit in communication with the oscillator circuit to modify the operating mode of the oscillator circuit.

WO 2023/224656 A1

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MODIFIABLE OSCILLATOR CIRCUIT FOR OPERATING MODES

RELATED PATENT APPLICATION

This application claims priority to commonly owned United States Patent Application No. 63/344,204 filed May 20, 2022, the entire contents of which are hereby incorporated by reference for all purposes.

TECHNICAL FIELD

The present disclosure relates to modifiable oscillator circuits for operating modes having different clock frequency accuracy and power consumption states.

BACKGROUND

Bluetooth is a specification published by Bluetooth SIG, Inc., of Kirkland, Washington, and utilizes low power radio. The specification defines a number of modes of operation, including a peripheral device in an advertising state, a peripheral device in a connection state, and a central device in a connection state. The frequency of low power resistor-capacitor (RC) oscillators may be inaccurate for scheduling Bluetooth connections, i.e. for operation in the connection state for both peripheral and central devices, but may be adequate for meeting the relaxed design constraints for timing advertising events, i.e. for peripheral device operation in the advertising state. For example, hearing aid applications require the use of accurate RC oscillators for the central device of +/-500ppm for scheduling Bluetooth connections, but medical implant applications may use less accurate RC oscillators (greater than 500ppm) for timing advertising events. For applications needing accurate RC oscillators, the limiting factor in the design may be the impact of Random Telegraph Noise (RTN). The magnitude of RTN in transistors can be reduced by increasing the area of the transistors, or by increasing the gate bias to move the operating region away from deep weak inversion, or by a combination thereof.

For many low power RC oscillators, the limiting factor on frequency accuracy may be the impact of RTN on the MOSFET transistors and not the impact of white noise or flicker noise. Unfortunately, increasing the area of the transistors alone may not reduce the RTN magnitude sufficiently and increasing the gate bias voltage of the transistors leads to an increase in the power consumption of the oscillator.

There is a need for a way to reduce power consumption in low power RC oscillators used for Bluetooth low energy radio operations, such as hearing aids and medical implants and at the same time meet the frequency accuracy requirements of the peripheral and central connection and advertising use cases.

SUMMARY OF THE INVENTION

The impact of RTN on low power RC oscillators used for Bluetooth Low Energy radio operations may be mitigated by modifying the transistor operating region between weak, moderate and strong inversion using a programmable circuit to maintain a predetermined frequency accuracy.

According to an aspect, there is provided a device comprising: an RC oscillator circuit modifiable between a first operating mode and a second operating mode, wherein the first operating mode has a first frequency accuracy and a first power consumption, wherein the second operating mode has a second frequency accuracy and a second power consumption, wherein the second frequency accuracy is more accurate than the first frequency accuracy and the second power consumption is higher than the first power consumption; and a control circuit in communication with the oscillator circuit to modify the operating mode of the oscillator circuit.

Another aspect provides a method comprising: generating a first clock signal with an oscillator circuit in a first operating mode; transmitting a message using the first clock signal; modifying the oscillator circuit from the first operating mode to a second operating mode; generating a second clock signal with the oscillator circuit in the second operating mode; and transmitting a message using the second clock signal.

According to another aspect, there is provided a system comprising: a power management circuit; a radio circuit electrically connected to the power management circuit, wherein the radio circuit outputs signals to an antenna; an oscillator circuit electrically connected to the power management circuit, wherein the oscillator circuit is modifiable between first and second operating modes, wherein the first operating mode has a first frequency accuracy and a first power consumption, wherein the second operating mode has second frequency accuracy and a second power consumption, wherein the second frequency accuracy is more accurate than the first frequency accuracy and the second power consumption is higher than the first power consumption; a control circuit electrically connected to the radio circuit, the power management circuit and the oscillator circuit, wherein the control circuit modifies the operating mode of the oscillator circuit; and a wake circuit electrically connected to the oscillator circuit and the power management circuit, wherein the wake circuit produces a signal to the power management circuit at least partially based on the operating mode of the oscillator circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

The figures illustrate example oscillator circuits and systems for use in low-power radio applications, such as Bluetooth applications.

FIGURE 1A illustrates a diagram of a reduced power RC oscillator circuit for a low power radio application containing three RC oscillators biased at one of three different levels.

FIGURE 1B illustrates a diagram of a reduced power RC oscillator circuit for a low power radio application containing two RC oscillators biased at one of two different levels.

FIGURE 1C illustrates a diagram of a reduced power RC oscillator circuit for a low power radio application containing one RC oscillator that can be biased into three different states.

FIGURE 1D illustrates a diagram of a reduced power RC oscillator circuit for a low power radio application containing one RC oscillator that can be biased into two different states.

FIGURE 2 illustrates timing diagrams for a central device transmission of a connection interval and a peripheral device reception window and deep sleep condition.

FIGURE 3A illustrates diagrams of three RC oscillators, respectively operating at different power consumptions.

FIGURE 3B illustrates diagrams of two RC oscillators operating respectively at different power consumptions.

FIGURE 3C illustrates a diagram of a variable RC oscillator operable at three different power consumption states or modes.

FIGURE 3D illustrates a diagram of a variable RC oscillator operable at two different power consumption states or modes.

FIGURE 3E illustrates a diagram of three RC oscillators, wherein two of the oscillators operate at different power consumptions and the third oscillator is a variable RC oscillator operable at two different power consumption states or modes.

FIGURE 4 illustrates one example of RTN in MOSFET devices causing frequency deviations in an RC oscillator.

FIGURE 5 illustrates one of various examples of RTN in a silicon channel interface.

FIGURE 6 illustrates one of various examples of the impact of RTN on the threshold voltage of a MOSFET device.

FIGURE 7 illustrates one of various examples of a model of RTN.

FIGURE 8 illustrates a device having an RC oscillator circuit and a control circuit.

FIGURE 9A illustrates a method for mitigating RTN by setting a device in an advertising state, operating an RC oscillator at a first power, changing the device to a connecting state, and operating the RC oscillator at a second power.

FIGURE 9B illustrates a method as in FIGURE 9A for changing the device to a central device in a connecting state and operating the RC oscillator at a third power.

FIGURE 10 illustrates a timing chart for advertising events based on an adverting interval and a randomly generated advertising delay.

FIGURE 11 illustrates a method for mitigating RTN by generating a first clock signal, transmitting a message using the first clock signal, modifying the oscillator circuit, generating a second clock signal, and transmitting a message using the second clock signal.

FIGURE 12A illustrates a bias voltage generator circuit having a transistor with a fixed transistor area of WxL that consumes a bias current of IBIAS, wherein the operating region of the transistor is in weak inversion.

FIGURE 12B illustrates a bias voltage generator circuit having a transistor with fixed area WxL and a switched bias current IBIAS or 2xIBIAS via a switch SW, wherein the circuit may be controllable to modify a transistor operating region of the transistor in the oscillator circuit.

FIGURE 12C illustrates a bias voltage generator circuit having two transistors with a fixed bias current IBIAS and a switched area of WxL or 2xWxL via a switch SW, wherein the circuit may be controllable to modify a transistor operating area of the transistors in the oscillator circuit.

FIGURE 12D illustrates a bias voltage generator circuit having two transistors with a fixed bias current IBIAS and a switched area of WxL or Wx2xL via a switch SW, wherein the circuit may be controllable to modify a transistor operating area of transistors in the oscillator circuit.

The reference number for any illustrated element that appears in multiple different figures has the same meaning across the multiple figures, and the mention or discussion herein of any illustrated element in the context of any particular figure also applies to each other figure, if any, in which that same illustrated element is shown.

DESCRIPTION

Power consumption may be reduced in low power RC oscillators used for radio transmissions, such as Bluetooth Low Energy radio operations, but not limited thereto, by modifying the transistor operating region or area between weak and strong inversion using a programmable bias in order to maintain a specified frequency accuracy.

Instead of using one fixed RC oscillator with a frequency accuracy of within +/- 500 parts per million (ppm), or another desired frequency accuracy, that consumes a particular level of power to maintain the desired frequency accuracy in the face of noise, including Random Telegraph Noise (RTN), either (1) a plurality of discrete RC oscillators tailored to meet power consumption/frequency accuracy trade-offs to address respective use cases, or (2) one RC oscillator that has two or three bias current/capacitance settings to control the power consumption/frequency accuracy trade-off to address each specific use case.

A low power RC oscillator may be used when low power mode, such as an advertising mode under the above mentioned Bluetooth specification, is implemented. A separate RC oscillator that is internally biased with a higher current and/or larger transistors in order to reduce the magnitude of RTN may be used in some applications where a higher average power consumption may be tolerated. This separate RC oscillator may be used when the mode of operation is to be accurately timed. In this way power consumption may be reduced when frequency accuracy tolerance is not a significant criteria and power consumption may increase when a mode that requires a tighter frequency accuracy tolerance is implemented, in particular, when the frequency tolerance is to be more accurate.

Random Telegraph Noise (RTN), also known as Random Telegraph Signals (RTS), is caused by channel charge carriers being trapped and released close to the transistor gate oxide to silicon channel interface. FIGURE 5 shows one of various examples of RTN in a silicon channel interface. When charge carriers are trapped there is a sudden drop in channel current and when released there is a sudden increase in channel current. These sudden ‘telegraphic’ events may occur with a frequency and magnitude that cannot be predicted and may lead to performance degradation in analog circuits. Low power circuits may be sensitive to RTN as the magnitude of channel current variation, i.e. ΔId/Id increases as the transistor is biased further into the weak inversion region (sub-threshold region). This is unfortunate for low power circuits that exploit an increase in transistor gain and low power consumption as this exploitation requires that the transistor be biased relatively deeply into the weak inversion region. FIGURE 6 shows one of various examples of the impact of RTN on the threshold voltage (Vt) of a MOSFET device, which shows an increase in Vt in response to a capture event, which increase is maintained for a period of time τ_e after which the charge is emitted. FIGURE 6 similarly shows this state is maintained for a period of time τ_c after which an additional capture event may occur.

The phenomena of RTN may be observed as a ΔId in the transistor channel and can be modelled as a ΔVt that is telegraphic in nature. FIGURE 7 shows one of various examples of a model of RTN. The magnitude of ΔVt is proportional to ~1/sqrt(Area). The impact of RTN is highest in weak inversion where the ΔId/Id increases due to a larger ratio of gm/Id, where gm represents the mutual conductance of the transistor in operation. The statistical distribution of ΔVt is modelled by an exponential distribution which suffers from a thick tail. RTN can end up being the dominant noise source in ultra-low power MOS circuit designs.

Bluetooth Low Energy, as specified by Bluetooth SIG, Inc., or Bluetooth LE, has two significant states of operation: the advertising state and the connection state. Implementations of a device meeting the Bluetooth LE specification may use a low power resistor-capacitor (RC) oscillator to act as a clock source with a timer to schedule advertising events and connection events. At the end of an advertising event or a connection event the timer can be set for a wake-up time and the device placed into a low power state (deep sleep). Once the timer wakes up the device from deep sleep, the device can advertise or connect and return back to deep sleep to preserve energy before the next wake-up time. RTN will impact the frequency accuracy of the oscillator and therefore the accuracy of when the wake-up timer wakes up the device from deep sleep.

A challenge for the circuit designer is to design an RC oscillator that uses a low power for a given voltage, e.g. a battery source, while meeting the required frequency accuracy.

The telegraphic nature of RTN in transistors, which may provide sudden steps of current in the MOSFET transistors, can significantly impact the frequency accuracy of low power RC oscillators. FIGURE 4 shows one example of RTN noise affecting the output frequency of a low power RC oscillator. Large frequency excursions of -4000ppm are observed on some of the devices. The average frequency accuracy across different devices, with respective RC oscillators, is 900ppm. Reducing RTN can be accomplished by increasing transistor operating area (to a point) or to operate the oscillator at higher power. However, higher power is a problem for ultra-low power designs for Bluetooth LE based radios, such as medical implants.

In one example, three discrete RC oscillators or one RC oscillator with three bias settings may be used in a radio, such as a Bluetooth LE based radio, to mitigate the impact of RTN for a peripheral device in an advertising state, a peripheral device in a connection state, and a central device in a connection state. In one example, a peripheral device may be a medical device implanted in a body and a central device may be a smart phone. In another example, a peripheral device may be a first hearing aid and the central device may be a second hearing aid paired with the first hearing aid, and at given times, the first and second hearing aids may switch roles so that the second hearing aid acts as the peripheral device and the first hearing aid acts as the central device. In still another example, a hearing aid may be a peripheral device and a smart phone may be a central device.

The advertising state may be an asynchronous mode of operation that does not require a high accuracy clock source, for example, an asynchronous communication mode. It is often desirable to utilize a very low deep sleep power consumption for the advertising state. For example, a medical implant in the advertising state, which advertises at five seconds (5s) intervals may have an average power consumption design constraint of ~1.2µW when a 1.2V voltage source is considered. An RC oscillator, which consumes 120nW in the deep sleep state, would take up 10% of the average power consumption design constraint.

The connection state may be a synchronous mode of operation where a peripheral device receive (RX) event is synchronized to coincide with a central transmit (TX) event, for example, a synchronous communication mode. The timing accuracy of the central device is required to be within +/-500ppm but the timing accuracy of the peripheral device may be more relaxed providing that sufficient RX window widening is used. Unfortunately, extra RX window widening leads to extra power consumption. It is therefore important to trade-off the power required to reduce RTN in an RC oscillator to set a certain frequency accuracy with the power consumption in the radio to support a certain RX window widening. Another consideration for the peripheral device in a connection state is that it often consumes more power than the peripheral device in an advertising state due to the higher rate of operation. For example, a hearing aid keep-a-live connection may have an average power consumption for connections events of ~12μW and ~60μW for 1 second & 100ms connection events, respectively, for a peripheral device using a 1.2V voltage source.

A first RC oscillator of the three discrete RC oscillators, or the single RC oscillator in a first of the three bias settings has the respective transistors biased into weak inversion in order to increase the transistor gain and reduce the power consumption. Because advertising events are asynchronous in nature according to an asynchronous communication mode, the time between advertising events does not have to be accurately set, and therefore a peripheral device in the advertising state may utilize the first RC oscillator or the single RC oscillator in the first bias setting. Elevated levels of RTN may cause elevated levels of frequency inaccuracy which may be tolerated without causing problems in meeting the relaxed timing constraints. An example of this is a medical implant that can be in deep sleep for 20 seconds or more between advertising events. Because the advertising events are infrequent the RC oscillator power can have a considerable impact on battery life and may contribute to more than 50% of the radio device power consumption while in the advertising state. Reducing the power consumption in the RC oscillator may extend the life of the product.

The second RC oscillator of the three discrete RC oscillators or the RC oscillator in a second of the three bias settings has the transistors biased in the weak to moderate inversion region, i.e. biased with an increased power consumption as compared to the first RC oscillator or the single RC oscillator in the first bias setting, in order to reduce the impact of RTN on the oscillator period, i.e. on the frequency accuracy. A peripheral device in the connection state may utilize the second RC oscillator of the single RC oscillator in the second bias setting. An example of this is a hearing aid device operating as a peripheral device that maintains a ‘keep alive’ radio connection with a connection interval of ~125ms. Because the time interval between connection events is typically shorter than for advertising events, the RC oscillator may consume a higher power and still be significantly less than the overall radio power consumption of the peripheral device. The frequency accuracy of the RC oscillator for the peripheral device can be designed such that the power consumption of the RC oscillator plus radio with RX window widening is reduced, and in some cases minimized.

The third RC oscillator of the three discrete RC oscillators or the RC oscillator in a third of the three bias settings has the transistors biased towards strong inversion, i.e. biased with an increased power consumption as compared to the second RC oscillator or the single RC oscillator in the second bias setting, to reduce the RTN to a level where the oscillator can be used in a central device to provide the specified frequency accuracy, e.g., within +/-500ppm.

FIGURE 1A shows the circuit 100 in various examples. A battery (VBATT) 102 provides power to a register circuit 104, a plurality of RC oscillators, labelled respectively (RCO1) 106, (RCO2) 108, and (RCO3) 110, a clock multiplexer 112, a wakeup timer or wake circuit 114, and a power management circuit 116. In this example, the register 104 and the clock multiplexer 112 combine to form a control circuit 122. The power management circuit 116 provides a VDD supply voltage to a microcontroller unit (MCU) 118, and a radio circuit 120. The radio circuit 120 may comprise an antenna 121 for transmitting a signal. The circuit 100 shown in FIGURE 1A may be implemented in either a peripheral device or a central device. The circuit 100, or portions thereof, may be implemented by instructions in storage medium for execution by a processor, a function, library call, subroutine, shared library, software as a service, analog circuitry, digital circuitry, control logic, digital logic circuits programmed through hardware description language, application-specific integrated circuit (ASIC), field-programmable gate array (FPGA), programmable logic device (PLD), or any suitable combination thereof, or any other suitable mechanism, whether in a unitary device or spread over several devices.

In operation, RC oscillator RCO1 106 may be enabled when the circuit is used in a peripheral device in the advertising state, with a typical power consumption of greater than 60nW and less than 480nW using a 1.2V voltage source, however this is not meant to be limiting. RC oscillator RCO2 108 may be enabled when the circuit is used in a peripheral device in the connection state, with a power consumption greater than the power consumption of RC oscillator RCO1 106, with a typical power consumption of greater than 0.48μW and less than 1.2μW using a 1.2V voltage source. RC oscillator RCO3 110 may be enabled when the circuit is used in a central device in the connection state, with a power consumption greater than the power consumption of RC oscillator RCO2 108, with a typical power consumption of greater than 1.2μW and less than 3μW using a 1.2V voltage source. The clock multiplexer 112 may select the enabled one of RC oscillators RCO1 106, RCO2 108 or RCO3 110 for output to the wakeup timer or wake circuit 114. The wakeup timer or wake circuit 114 provides a signal to activate the power management circuit 116. The power management circuit 116 may provide the supply voltage VDD to the MCU 118 and radio circuit 120, at least partially in response to the provided signal to activate the power management circuit 116. Firmware in the MCU 118 may know if the system is a central or peripheral device and whether the device is in an advertising or connection state and enable the appropriate RC oscillator by loading the register circuit 104 with the appropriate value. The register circuit 104, at least partially responsive to the loaded value, may enable one of RC oscillators RCO1 106, RCO2 108, and RCO3 110 via the respective enable inputs. The register circuit 104, at least partially responsive to the loaded value, may send a signal to the clock multiplexer 112 to pass the enabled one of RC oscillators RCO1 106, RCO2 108, and RCO3 110 to the wake-up timer or wake circuit 114. In operation, when RC oscillator RCO1 106 is enabled and passed by the clock multiplexer 112, the radio 120 provides signals in according with timing as a peripheral in the advertising state. The timing of wake-up events may not require a predetermined frequency accuracy. When RC oscillator RCO2 108 is enabled and passed, the radio 120 provides signals in accordance with timing as a peripheral device operating in the connection state. Timing of wake-up events may be synchronized to occur during the connection interval, as shown in FIGURE 2. When RC oscillator RCO3 110 is enabled and passed, the radio 120 provides signals in accordance with timing as a central device operating in the connection state. RC oscillator RCO3 110 may provide the frequency accuracy required by the respective specification. In one of various examples, a timing accuracy tolerance of +/-500ppm may be the required frequency accuracy for the central device operating in the connection state when operating in a Bluetooth Low Energy (BLE) system.

FIGURE 1B shows the circuit 100 having two RC oscillators RCO1 and RCO2. In operation, RC oscillator RCO1 106 may be enabled when the circuit is used in a peripheral device in the advertising state, with a typical power consumption of greater than 60nW and less than 480nW using a 1.2V voltage source, however this is not meant to be limiting. RC oscillator RCO2 108 may be enabled when the circuit is used in a peripheral or central device in the connection state, with a power consumption greater than the power consumption of RC oscillator RCO1 106, with a typical power consumption of greater than 1.2μW and less than 3μW using a 1.2V voltage source.

FIGURE 1C shows the circuit 200 in another example. A battery (VBATT) 202 provides power to a programmable RC oscillator 205, labelled RCO, a wakeup timer 214, and a power management circuit 216. The power management circuit 216 provides a VDD supply voltage to a microcontroller unit (MCU) 218, and a radio circuit 220, at least partially responsive to a signal from wakeup timer 214. The circuit 200 shown in FIGURE 1C may be implemented in either a peripheral device or a central device. The circuit 200 may be implemented at least partially by instructions in storage medium for execution by a processor, a function, library call, subroutine, shared library, software as a service, analog circuitry, digital circuitry, control logic, digital logic circuits programmed through hardware description language, application-specific integrated circuit (ASIC), field-programmable gate array (FPGA), programmable logic device (PLD), or any suitable combination thereof, or any other suitable mechanism, whether in a unitary device or spread over several devices. The programmable RC oscillator RCO 205 may operate in a peripheral advertising state (State A), a peripheral connection state (State B), or a central connection state (State C). A signal from the MCU 218 may select either the peripheral advertising state (State A), the peripheral connection state (State B) or the central connection state (State C). Circuitry of programmable RC oscillator RCO 205 may select a different bias condition based on the MCU signal to keep the RC oscillator RCO frequency accuracy appropriate for the correct state A, B or C.

FIGURE 1D shows the circuit 200 in another example, which may be implemented in a peripheral device. The programmable RC oscillator RCO 205 may operate in a peripheral advertising state (State A) or a peripheral or central connection state (State B). A signal from the MCU 218 may select either the peripheral advertising state (State A) or the peripheral or central connection state (State B). Circuitry of programmable RC oscillator RCO 205 may select a different bias condition based on the MCU signal to keep the RC oscillator RCO frequency accuracy appropriate for the correct state A or B.

FIGURE 2 shows a timing diagram of a connection interval for a central device in the connection state that transmits a signal at a predefined Anchor Point time and a window for preamble detection by a peripheral device in the connection state. In a Bluetooth application, the central device may meet a timing accuracy of +/-500ppm per connection. The peripheral may enter a deep sleep mode between connection events. The peripheral may provide window widening proportional to the TX timing accuracy (TX acc) + RX timing accuracy (RX acc). The peripheral radio power consumption will be higher as the timing accuracy TX acc + RX acc increases.

FIGURE 3A shows three types of RC oscillators. RC oscillator RCO1 may be used by a peripheral device operating in an advertising state. RC oscillator RCO1 may be used for example in a medical implant use case where low power is an important design criteria. A power consumption may be greater than 60nW and less than 480nW using a 1.2V voltage source for RC oscillator RCO1. Alternatively, a power consumption may be ~120nW using a 1.2V voltage source for the RC oscillator RCO1 with a frequency accuracy less accurate than +/-500ppm such as +/-4000ppm. The transistors in RC oscillator RCO1 may be biased in weak inversion to improve the transistor gain and to reduce power consumption. Advertising may be by nature an asynchronous event and therefore does not require an accurate time base, i.e. does not require frequency accuracy.

RC Oscillator RCO2 may be used in a peripheral device operating in a connection state. RC oscillator RCO2 may be used for example in a hearing aid for keep alive connection with reduced power consumption. A power consumption could be greater than 480nW and less than 1.2 µW using a 1.2V voltage source for RC oscillator RCO2. Alternatively, a power consumption could be ~600nW using a 1.2V voltage source for RC oscillator RCO2. The transistors in RC oscillator RCO2 may be biased in the weak to moderate inversion region to reduce the impact of RTN and keep power consumption low. The peripheral device may have a clock frequency accuracy less accurate than +/-500ppm, such as +/-600ppm. Alternatively, the clock frequency of the peripheral device may be more accurate, such as +/-400ppm. The average connection power consumption can be established based on two variables - RC oscillator power consumption to support a predetermined frequency accuracy and RX power consumption impacted by extra window widening to compensate for the difference between the required frequency accuracy and the provided frequency accuracy.

RC Oscillator RCO3 may be used in a central device operating in the connection state. RC Oscillator RCO3 may be used for example in a hearing aid acting as the central device for keep alive connection. A power consumption may be greater than 1.2µW and less than 3µW using a 1.2V voltage source for RC Oscillator RCO3. Alternatively, a power consumption may be ~2.4µW using a 1.2V voltage source for the RC Oscillator RCO3. The transistors in RCO3 may be biased in the moderate to strong inversion region reduce the impact of RTN. In a Bluetooth application, the RC oscillator RCO3 may meet the +/-500ppm frequency accuracy tolerance.

FIGURE 3B shows two types of RC oscillators. RC oscillator RCO1 may be used by a peripheral device operating in an advertising state. A power consumption may be greater than 60nW and less than 480nW using a 1.2V voltage source for RC oscillator RCO1. Alternatively, a power consumption may be ~120nW using a 1.2V voltage source for the RC oscillator RCO1 with a frequency accuracy less accurate than +/-500ppm such as +/-4000ppm. The transistors in RC oscillator RCO1 may be biased in weak inversion to improve the transistor gain and to reduce power consumption. RC Oscillator RCO2 may be used in the peripheral or central device operating in a connection state. A power consumption could be greater than 1.2μW and less than 3 μW using a 1.2V voltage source for RC oscillator RCO2. Alternatively, a power consumption could be ~2.4μW using a 1.2V voltage source for RC oscillator RCO2. The peripheral or central device may have a clock frequency accuracy within +/-500 ppm.

FIGURE 3C shows a variable RC Oscillator, RC Oscillator RCO4, which may be utilized in a peripheral device operating in the advertising state, the peripheral device operating in the connection state, and in a central device operating in the connection state. Mode_sel signal may select either the peripheral device advertising state (state A), the peripheral device connection state (state B) or the central device connection state (state C). Circuitry of RC Oscillator RCO4 may select a different bias condition based on the setting of mode_sel to keep the RC Oscillator RCO4 frequency accuracy appropriate for the correct state A, B or C. For example, state A may be selected to set a power consumption greater than 60nW and less than 480nW using a 1.2V voltage source for RC Oscillator RCO4. Alternatively, state A may set a power consumption ~120nW using a 1.2V voltage source for the RC Oscillator RCO4. Selection of state B may set power consumption greater than 480nW and less than 1.2μW using a 1.2V voltage source for RC Oscillator RCO4. Alternatively, state B may set a power consumption ~600nW using a 1.2V voltage source for the RC Oscillator RCO4. Selection of state C may set a power consumption greater than 1.2μW and less than 3μW using a 1.2V voltage source for RC Oscillator RCO4. Alternatively, state C may set a power consumption ~2.4μW using a 1.2V voltage source for the RC Oscillator RCO.

FIGURE 3D shows a variable RC Oscillator, RC Oscillator RCO4, which may be utilized in a peripheral device operating in the advertising state or connection state. Mode_sel signal may select either the peripheral device advertising state (state A) or the peripheral or central device connection state (state B). Circuitry of RC Oscillator RCO4 may select a different bias condition based on the setting of mode_sel to keep the RC Oscillator RCO4 frequency accuracy appropriate for the correct state A or B. For example, state A may be selected to set power consumption greater than 60nW and less than 480nW using a 1.2V voltage source for RC Oscillator RCO4. Alternatively, state A may set power consumption ~120nW using a 1.2V voltage source for the RC Oscillator RCO4. Selection of state B may set power consumption greater than 1.2μW and less than 3μW using a 1.2V voltage source for RC Oscillator RCO4. Alternatively, state B may set power consumption ~2.4μW using a 1.2V voltage source for the RC Oscillator RCO4.

FIGURE 3E shows three types of RC oscillators. RC oscillator RCO1 may be used by a peripheral device operating in an advertising state. Power consumption may be greater than 60nW and less than 480nW using a 1.2V voltage source for RC oscillator RCO1. Alternatively, power consumption may be ~120nW using a 1.2V voltage source for the RC oscillator RCO1 with a frequency accuracy less accurate than +/-500ppm such as +/-4000ppm. The transistors in RC oscillator RCO1 may be biased in weak inversion to improve the transistor gain and to reduce power consumption. RC Oscillator RCO2 may be used in the peripheral or central device operating in a connection state. Power consumption could be greater than 1.2μW and less than 3 μW using a 1.2V voltage source for RC oscillator RCO2. Alternatively, power consumption could be ~2.4μW using a 1.2V voltage source for RC oscillator RCO2. The peripheral or central device may have a clock frequency accuracy within +/-500ppm. RC Oscillator RCO3, which may be utilized in a peripheral device operating in the advertising state or connection state. Mode_sel signal may select either the peripheral device advertising state (state A) or the peripheral or central device connection state (state B). Circuitry of RC Oscillator RCO3 may select a different bias condition based on the setting of mode_sel to keep the RC Oscillator RCO3 frequency accuracy appropriate for the correct state A or B. For example, state A may be selected to set power consumption greater than 60nW and less than 480nW using a 1.2V voltage source for RC Oscillator RCO3. Alternatively, state A may set power consumption ~120nW using a 1.2V voltage source for the RC Oscillator RCO3. Selection of state B may set power consumption greater than 1.2μW and less than 3μW using a 1.2V voltage source for RC Oscillator RCO3. Alternatively, state B may set power consumption ~2.4μW using a 1.2V voltage source for the RC Oscillator RCO3.

FIGURE 8 illustrates a device that has a RC oscillator circuit 805 and a control circuit 822.

FIGURE 9A illustrates a method for setting 902 a peripheral device in an advertising state, operating 904 an RC oscillator at a first bias state, changing 906 the device to a peripheral device in a connecting state, and operating 908 the RC oscillator at a second bias state.

FIGURE 9B illustrates an alternative method that may include changing 910 the device to a central device in a connecting state, and operating 912 the RC oscillator at a third bias state. For the methods of FIGURES 9A and 9B, there is no requirement that the flow be in any particular order, and thus a peripheral device in the advertising state may change to a central device in the connecting state, i.e. to operating the RC oscillator at the third bias state without exceeding the scope. Similarly, the methods may include changing the device from the second bias state to the first bias state, or changing the device from the third bias state to the first bias state.

In one example, the device may be selected from a low power peripheral radio device and a low power central radio device, and an operating state may be selected from a radio advertising state, a peripheral radio connection state, and a central radio connection state, with respective power consumption and frequency accuracy.

FIGURE 10 illustrates a timing chart for advertising events. An advertising state may be initiated by a peripheral device. It may send data on predetermined channels, e.g., channels 37/38/39, to whatever other devices may be listening. The data may be an advertising message, the transmission of the advertising message may be an advertising event. An advertising event may be an asynchronous event, such that there may be an advertising period (T_advEvent) between subsequent advertising events, with a random time component (advDelay) according to an asynchronous communication mode as shown. In this context, asynchronous means that the peripheral can initiate an advertising message at any time and the advertising period is thus, from a receiver's (i.e. central device's) standpoint, random. A central device may be listening to the predetermined channels, so that the advertising event may occur at any particular point in absolute time. The peripheral device may have no a priori knowledge of when the central device is listening. The advertising period may determine the time between subsequent transmission of an advertising message. Thus, the accuracy of the advertising period is not critical. Once a connection is established, the timing between the central device and the peripheral device may be synchronized. A relaxed clock accuracy may be used to conserve power in the deep sleep interval in the peripheral device when in the advertising state.

FIGURE 11 illustrates a method for generating 1102 a first clock signal with an oscillator circuit in a first operating mode, transmitting 1104 a message using the first clock signal, modifying 1106 the oscillator circuit from the first operating mode to a second operating mode, generating 1108 a second clock signal with the oscillator circuit in the second operating mode, and transmitting 1110 a message using the second clock signal.

Although examples have been described above, other variations and examples may be made from this disclosure without departing from the spirit and scope of these disclosed examples.

FIGURE 12A shows a bias voltage generator circuit 300 having a transistor 301 with a fixed transistor area of WxL that consumes a bias current of IBIAS. The operating region of the transistor is in weak inversion.

FIGURE 12B shows a bias voltage generator circuit 300 having a transistor 301 with fixed area WxL and a switched bias current IBIAS or 2xIBIAS via a switch SW. The operating region of the transistor depends on the bias current and is in weak inversion with a bias current of IBIAS or moderate inversion with a bias current of 2xIBIAS. The magnitude of RTN may be reduced when the operating region changes from weak inversion to moderate inversion. This bias voltage generator circuit 300 may be controllable to modify a transistor operating region of transistor 301 in the oscillator circuit.

FIGURE 12C shows a bias voltage generator circuit 300 having two transistors 301 and 302 with a fixed bias current IBIAS and a switched area of WxL or 2xWxL via a switch SW, which when closed places transistors 301 and 302 in parallel. The operating region of the transistor depends on the width over length ratio and will be in weak inversion for a ratio of W/L and will be in deeper weak inversion for a ratio of 2xW/L. The magnitude of RTN may be reduced due to the increase in area but may also be increased due to the operating region changing from weak inversion to deeper weak inversion. This circuit may not be a solution for reducing RTN when transistor area is increased. This bias voltage generator circuit 300 may be controllable to modify a transistor operating area of transistors 301 and 302 in the oscillator circuit.

FIGURE 12D shows a bias voltage generator circuit 300 having two transistors 301 and 302 with a fixed bias current IBIAS and a switched area of WxL or Wx2xL via a switch SW which when closed places transistors 301 and 302 in series, with a common gate. The operating region of the transistor may depend on the width over length ratio and may be in weak inversion for a ratio of W/L and may be in moderate inversion for a ratio of W/(2xL). The magnitude of RTN may be reduced due to the increase in area and may also be reduced due to the operating region changing from weak inversion to moderate inversion. This circuit may be a solution for reducing RTN when transistor area is increased. This bias voltage generator circuit 300 may be controllable to modify a transistor operating area of transistors 301 and 302 in the oscillator circuit.

CLAIMS

1. A device comprising:

a resistor-capacitor oscillator circuit modifiable between a first operating mode and a second operating mode,

wherein the first operating mode has a first frequency accuracy and a first power consumption,

wherein the second operating mode has a second frequency accuracy and a second power consumption,

wherein the second frequency accuracy is more accurate than the first frequency accuracy and the second power consumption is higher than the first power consumption; and

a control circuit in communication with the oscillator circuit to modify the operating mode of the oscillator circuit.

2. The device as claimed in claim 1, wherein the first operating mode comprises a weak inversion mode and the second operating mode comprises a weak to moderate inversion mode, wherein in the second operating mode, the resistor-capacitor oscillator circuit is to generates less random telegraph noise than the first operating mode.

3. The device as claimed in any of claims 1-2, wherein the oscillator circuit comprises two discrete resistor-capacitor oscillators and the control circuit is to modify the operating mode by selecting between the two discrete resistor-capacitor oscillators.

4. The device as claimed in any of claims 1-3, wherein the oscillator circuit comprises a programmable resistor-capacitor oscillator that has two bias current settings and the control circuit is to modify the operating mode by selecting between the two bias current settings.

5. The device as claimed in any of claims 1-4, wherein the oscillator circuit comprises a third operating mode, wherein the third operating mode has a third frequency accuracy and a third power consumption, wherein the third frequency accuracy is more accurate than the second frequency accuracy and the third current consumption is higher than the second current consumption.

6. The device as claimed in claim 5, wherein the third operating mode comprises a moderate to strong inversion mode.

7. The device as claimed in any of claims 5-6, wherein the first power consumption is between 60nW and 480nW, wherein the second power consumption is greater than 480nW and less than 1.20μW, and wherein the third power consumption is greater than 1.2μW and less than 3μW.

8. The device as claimed in any of claims 5-7, wherein the third frequency accuracy tolerance is +/- 500 ppm.

9. The device as claimed in any of claims 1-8, wherein the device is a peripheral device, and wherein the first operating mode is an advertising state and the second operating mode is a connection state.

10. The device as claimed in any of claims 1-8, wherein the device is selected from a low power peripheral radio device and a low power central radio device, and wherein the first operating mode is a radio advertising state, the second operating mode is a radio connection state, and the third operating mode is a radio connection state.

11. A method comprising:

generating a first clock signal with an oscillator circuit in a first operating mode;

transmitting a message using the first clock signal;

modifying the oscillator circuit from the first operating mode to a second operating mode;

generating a second clock signal with the oscillator circuit in the second operating mode; and

transmitting a message using the second clock signal.

12. The method as claimed in claim 11, wherein the first operating mode comprises an asynchronous communication mode.

13. The method as claimed in any of claims 11-12, wherein modifying the oscillator circuit comprises setting the oscillator circuit transistors into weak inversion to consume power by the oscillator circuit greater than 60nW and less than 480nW.

14. The method as claimed in any of claims 11-13, wherein the second operating mode comprises a synchronous communication mode in a peripheral device.

15. The method as claimed in claim 14, wherein modifying the oscillator circuit comprises operating the oscillator circuit transistors into weak to moderate inversion so as to consume power by the oscillator circuit greater than 480nW and less than 1.20μW.

16. The method as claimed in any of claims 11-15, comprising:

modifying the oscillator circuit from the second operating mode to a third operating mode;

generating a third clock signal with the oscillator circuit in the third operating mode; and

transmitting a message using the third clock signal.

17. The method as claimed in claim 16, wherein the third operating mode comprises a synchronous communication mode in a central device.

18. The method as claimed in any of claims 16-17, wherein modifying the oscillator circuit comprises setting the oscillator circuit transistors into moderate to strong inversion so as to consume power by the oscillator circuit greater than 1.2μW and less than 3μW and meet a frequency accuracy within +/-500ppm.

19. A system comprising:

a power management circuit;

a radio circuit electrically connected to the power management circuit, wherein the radio circuit is to output signals to an antenna;

an oscillator circuit electrically connected to the power management circuit, wherein the oscillator circuit is modifiable between first and second operating modes, wherein the first operating mode has a first frequency accuracy and a first power consumption, wherein the second operating mode has second frequency accuracy and a second power consumption, wherein the second frequency accuracy is more accurate than the first frequency accuracy and the second power consumption is higher than the first power consumption;

a control circuit electrically connected to the radio circuit, the power management circuit and the oscillator circuit, wherein the control circuit is to modify the operating mode of the oscillator circuit; and

a wake circuit electrically connected to the oscillator circuit and the power management circuit, wherein the wake circuit is to produce a signal to the power management circuit at least partially based on the operating mode of the oscillator circuit.

20. The system as claimed in claim 19, wherein the oscillator circuit comprises two discrete resistor-capacitor oscillators and the control circuit is to modify the operating mode by selecting between the two discrete resistor-capacitor oscillators.

21. The system as claimed in claim 19, wherein the oscillator circuit comprises a resistor-capacitor oscillator that has two bias settings and the control circuit modifies the operating mode by selecting between the two bias settings.

22. The system as claimed in claim 20, wherein the oscillator circuit is controllable to modify a transistor operating area in the oscillator circuit.

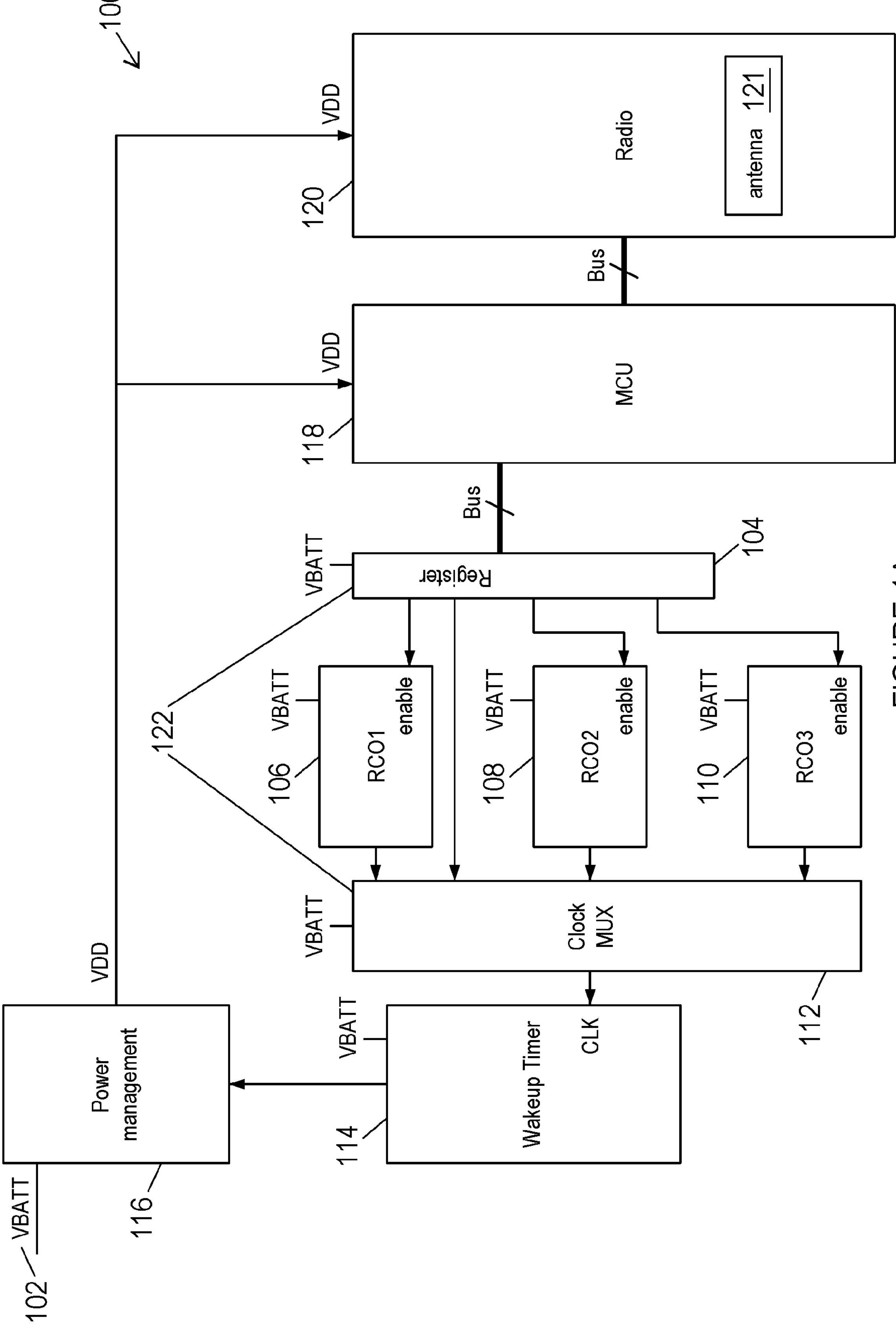

100
Radio
antenna 121
120
VDD
Bus
MCU
118
VDD
Bus
Register
104
VBATT
122
RCO1
enable
106
VBATT
RCO2
enable
108
VBATT
RCO3
enable
110
VBATT
Clock MUX
VBATT
112
VDD
Wakeup Timer
CLK
VBATT
114
Power management
116
VBATT
102

FIGURE 1A

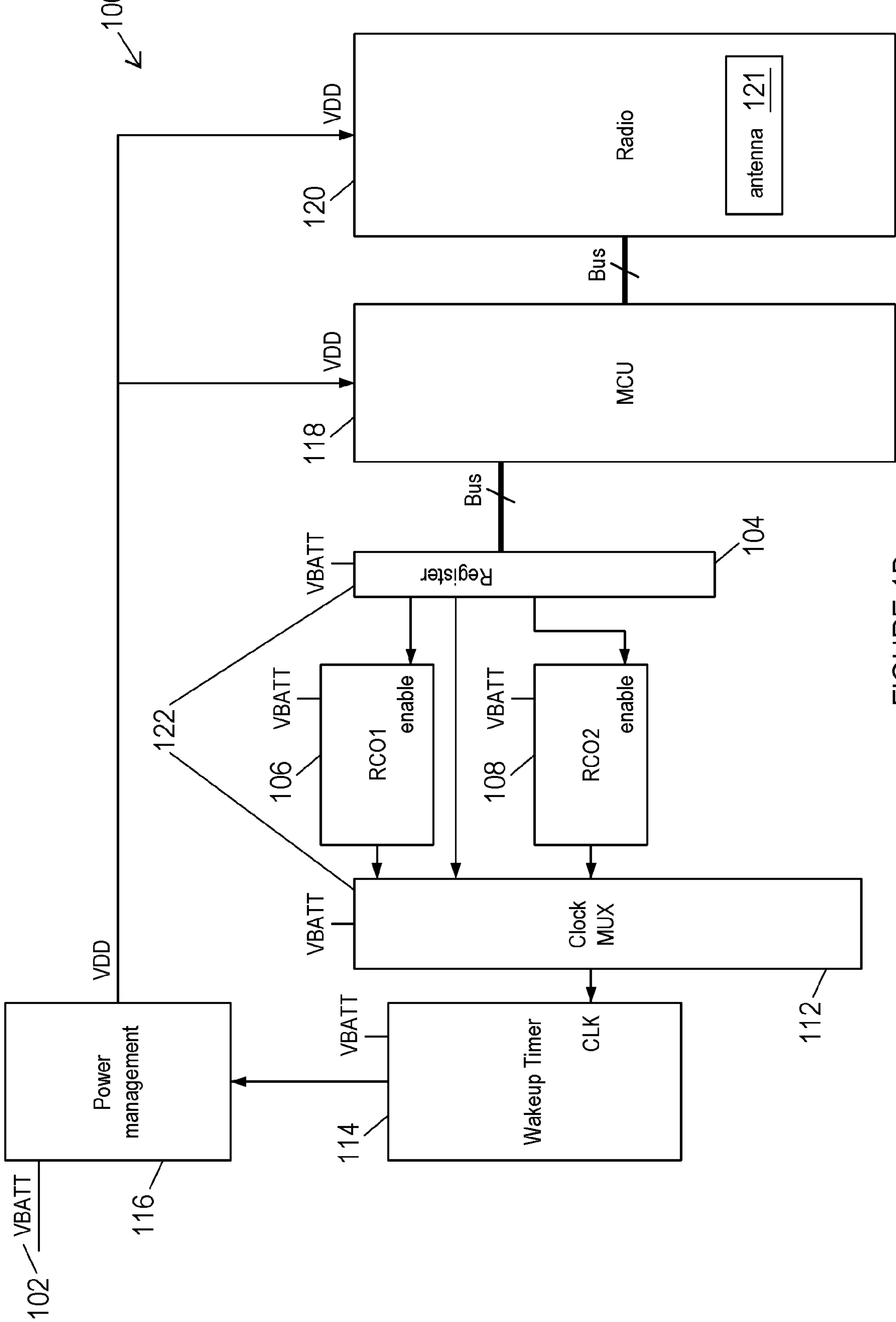

100
Radio
antenna 121
120
VDD
Bus
MCU
118
VDD
Bus
Register
104
VBATT
122
RCO1
enable
106
VBATT
RCO2
enable
108
VBATT
Clock
MUX
VBATT
112
Wakeup Timer
CLK
VBATT
114
Power
management
VDD
116
VBATT
102

FIGURE 1B

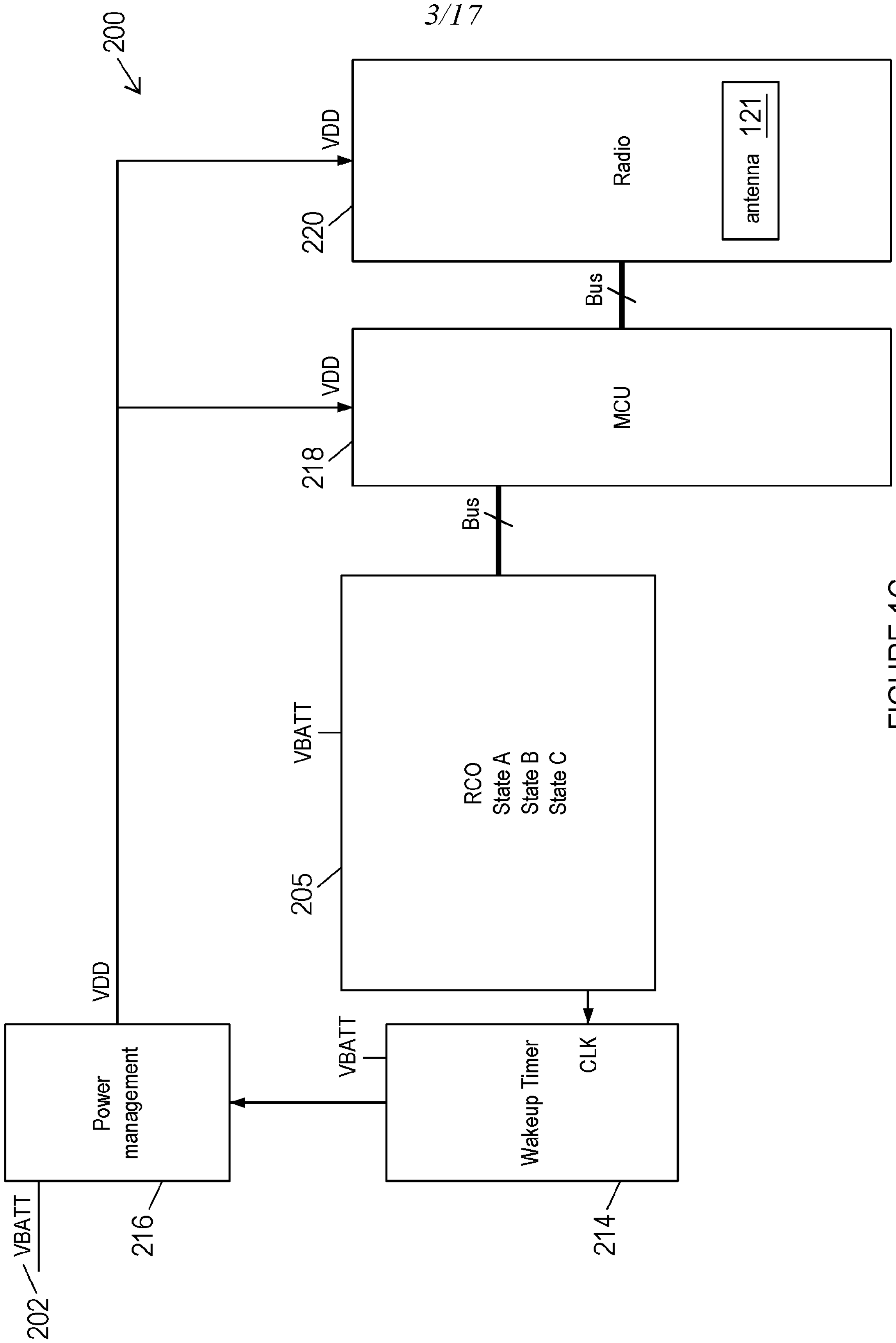

200
Radio
antenna 121
220
VDD
Bus
MCU
218
VDD
Bus
RCO
State A
State B
State C
205
VBATT
VDD
Power management
216
VBATT
202
Wakeup Timer
CLK
VBATT
214

FIGURE 1C

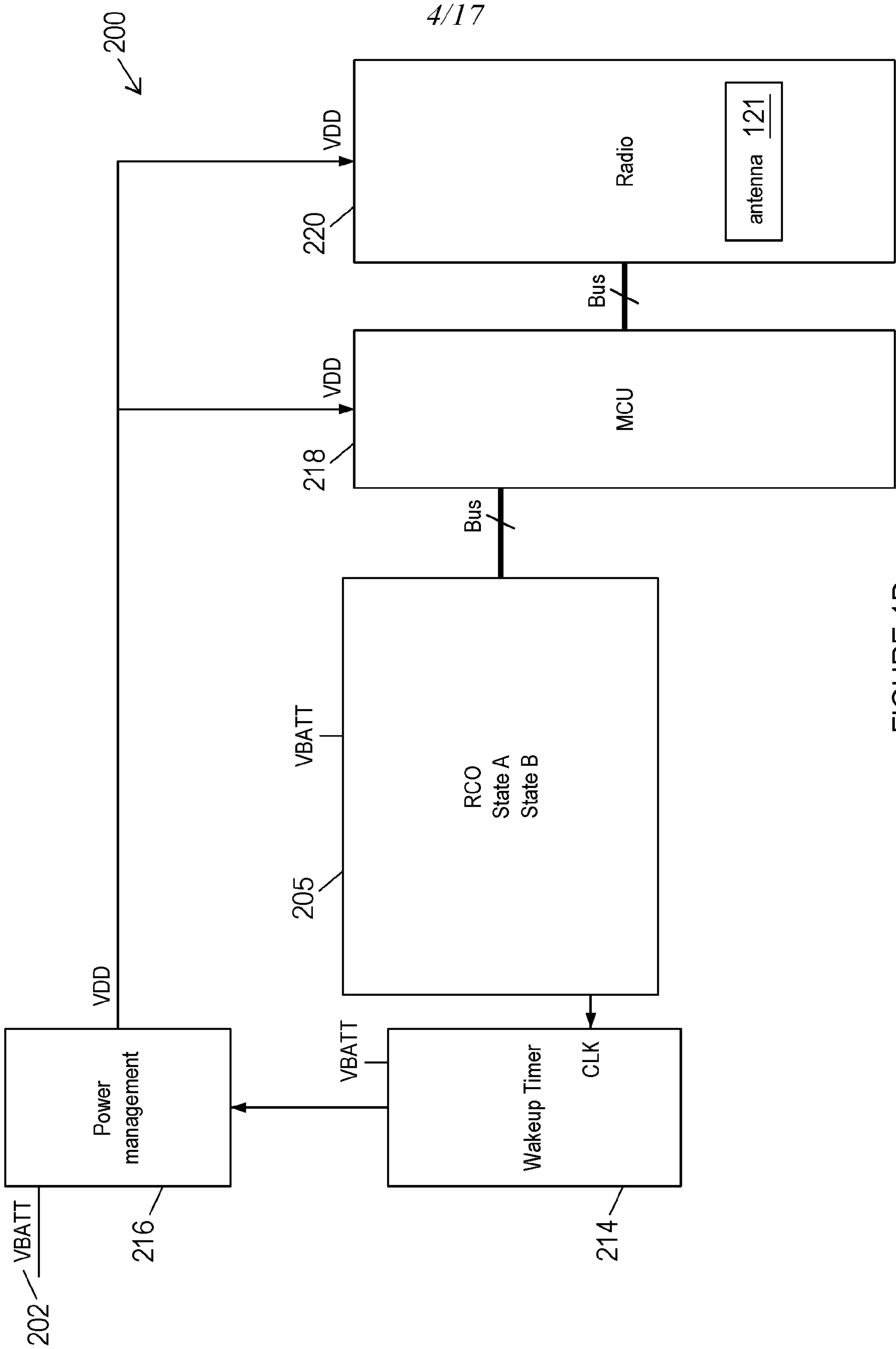

200
Radio
antenna 121
220
VDD
Bus
MCU
218
VDD
Bus
RCO
State A
State B
205
VBATT
VDD
Power management
216
VBATT
202
Wakeup Timer
CLK
VBATT
214

FIGURE 1D

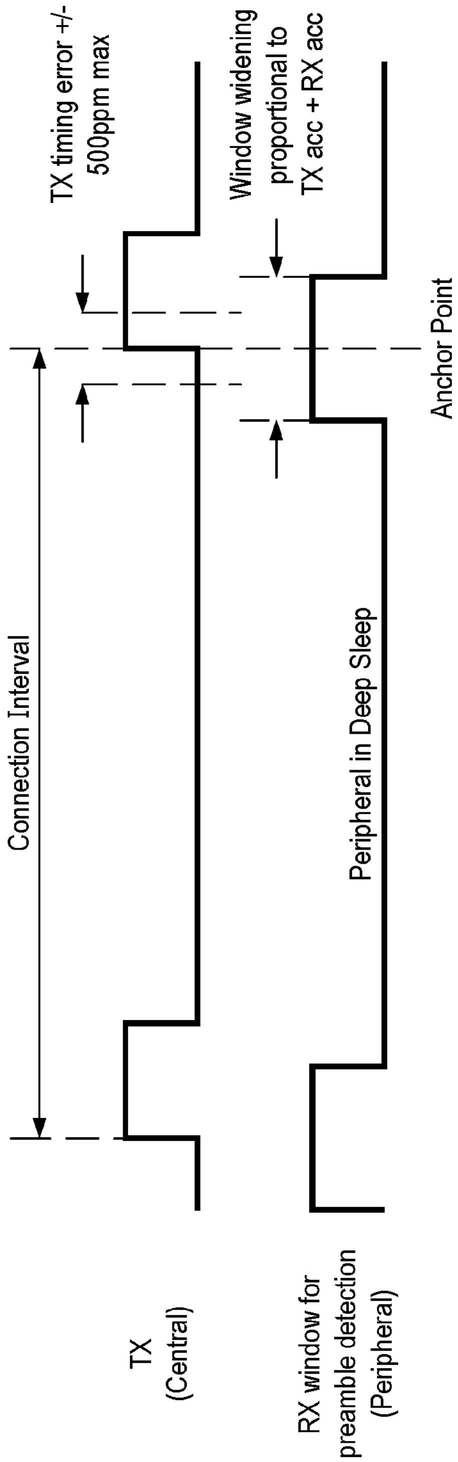

TX timing error +/- 500ppm max
Window widening proportional to TX acc + RX acc
Anchor Point
Connection Interval
Peripheral in Deep Sleep
TX (Central)
RX window for preamble detection (Peripheral)

FIGURE 2

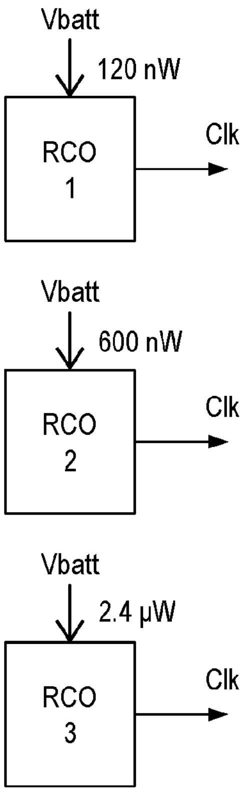


FIGURE 3A

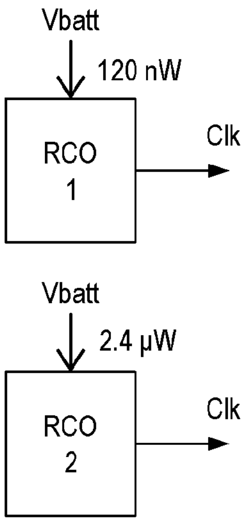


FIGURE 3B

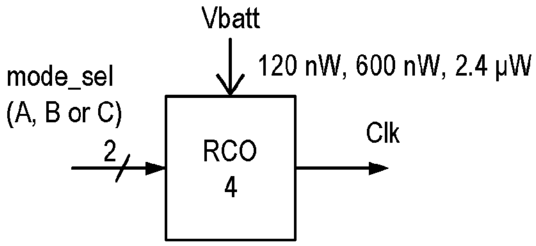


FIGURE 3C

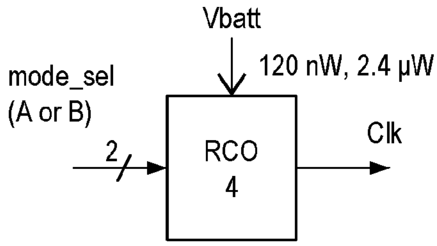


FIGURE 3D

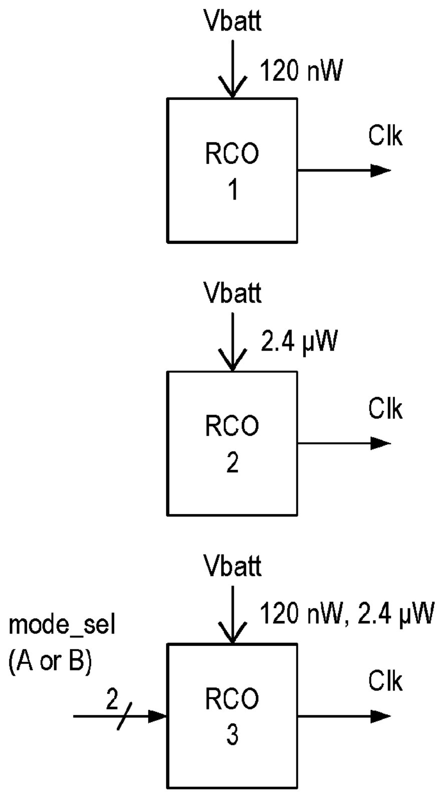


FIGURE 3E

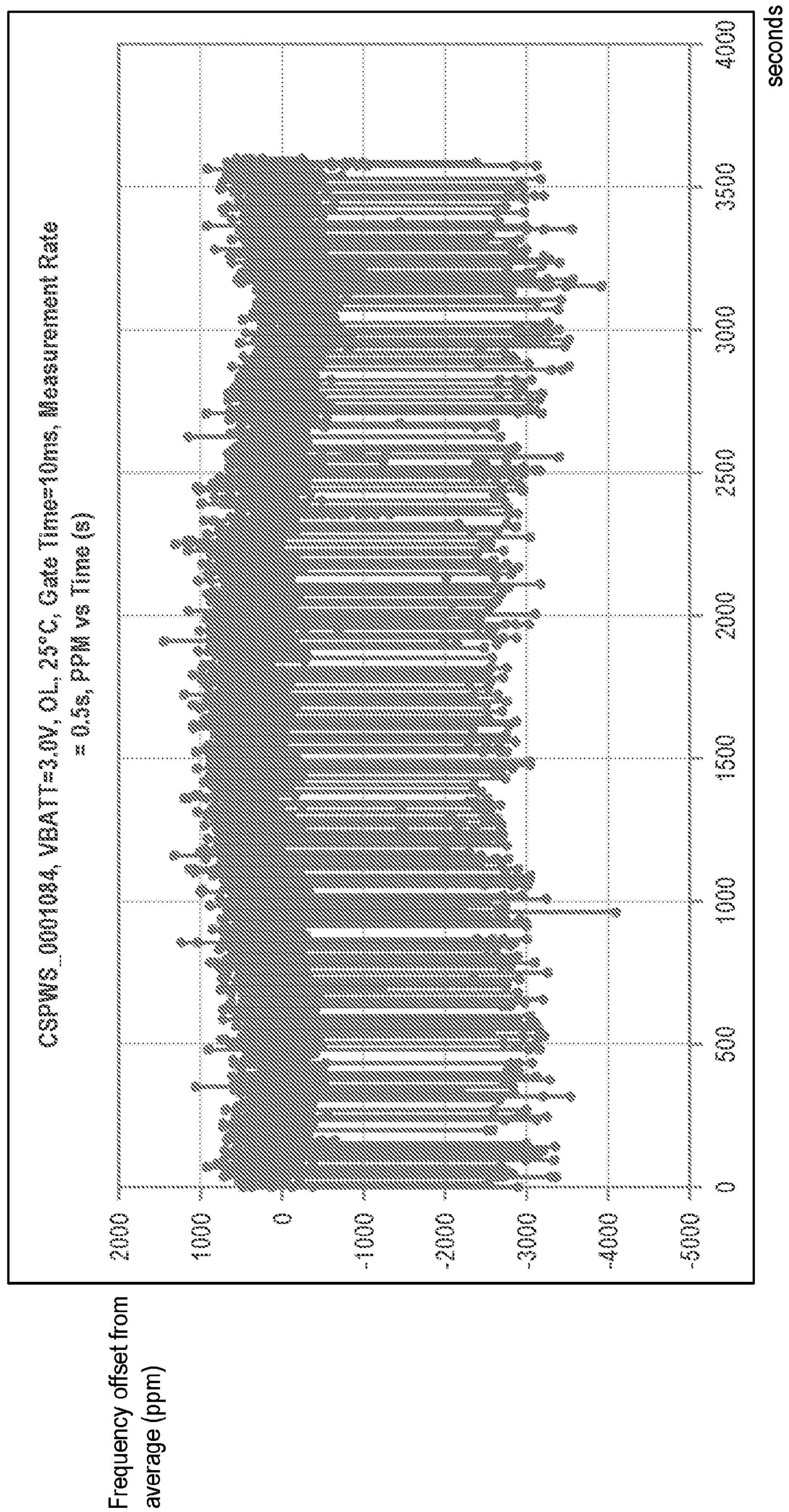

CSPWS_0001084, VBATT=3.0V, OL, 25°C, Gate Time=10ms, Measurement Rate = 0.5s, PPM vs Time (s)
Frequency offset from average (ppm)
2000
1000
0
-1000
-2000
-3000
-4000
-5000
0
500
1000
1500
2000
2500
3000
3500
4000
seconds

FIGURE 4

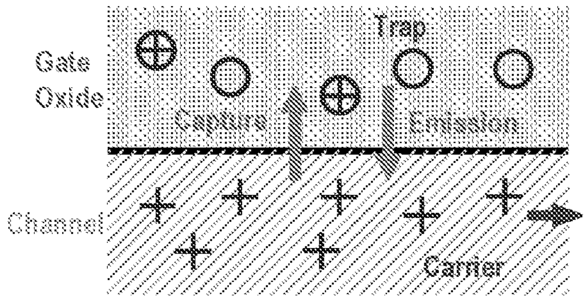


FIGURE 5

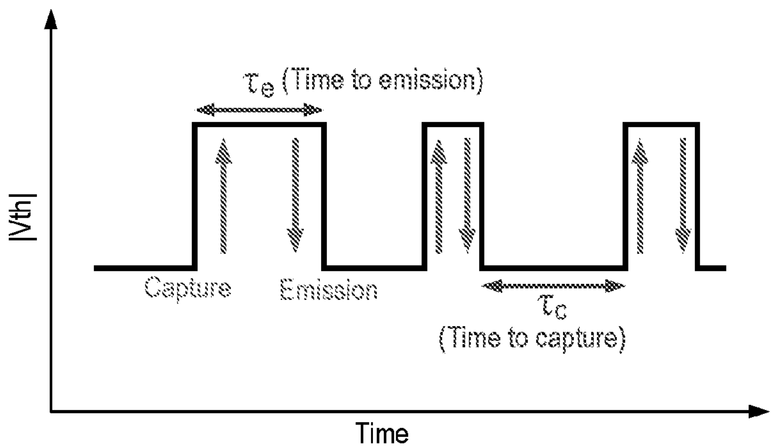


FIGURE 6

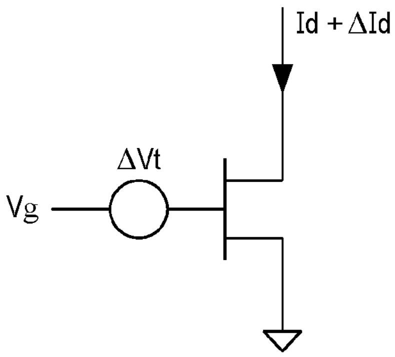


FIGURE 7

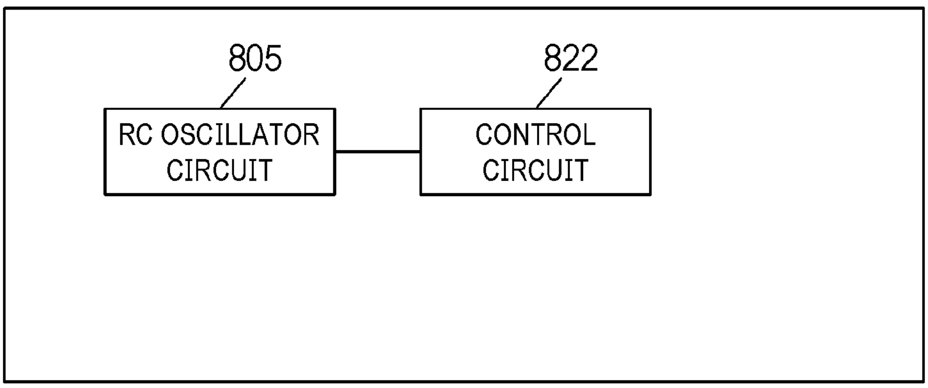


FIGURE 8

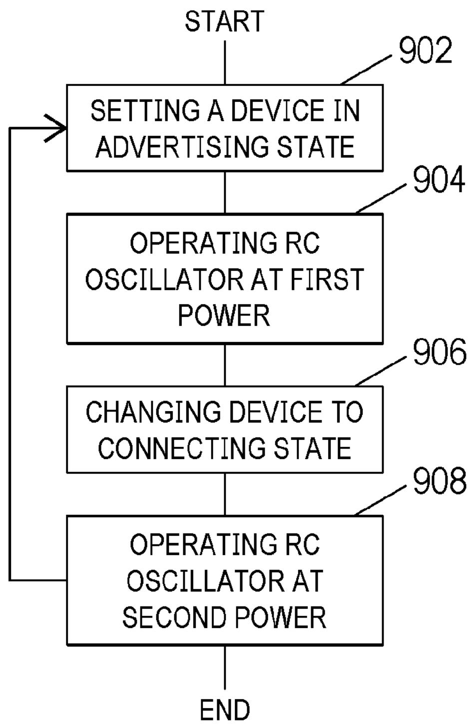

START
902
SETTING A DEVICE IN ADVERTISING STATE
904
OPERATING RC OSCILLATOR AT FIRST POWER
906
CHANGING DEVICE TO CONNECTING STATE
908
OPERATING RC OSCILLATOR AT SECOND POWER
END

FIGURE 9A

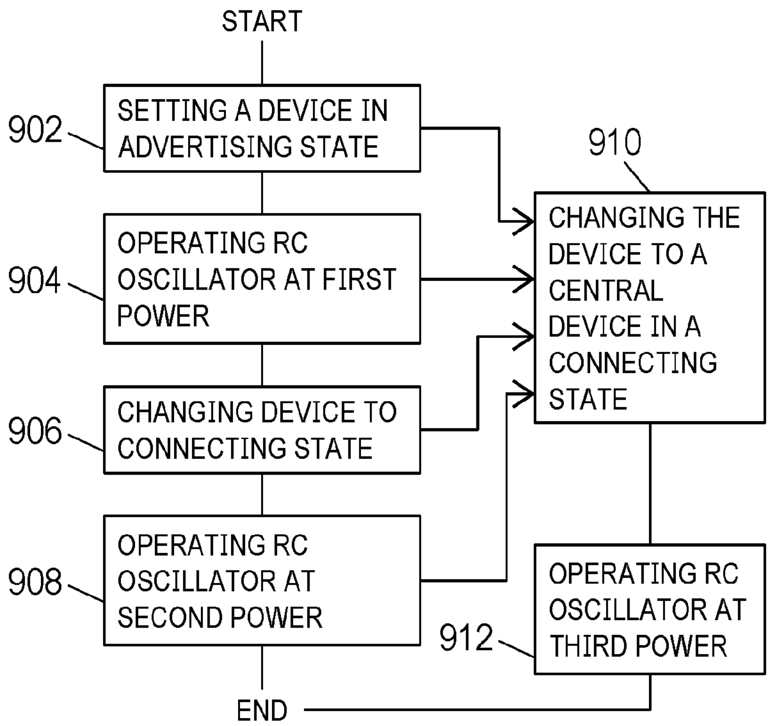

START
902
SETTING A DEVICE IN ADVERTISING STATE
904
OPERATING RC OSCILLATOR AT FIRST POWER
906
CHANGING DEVICE TO CONNECTING STATE
908
OPERATING RC OSCILLATOR AT SECOND POWER
910
CHANGING THE DEVICE TO A CENTRAL DEVICE IN A CONNECTING STATE
912
OPERATING RC OSCILLATOR AT THIRD POWER
END

FIGURE 9B

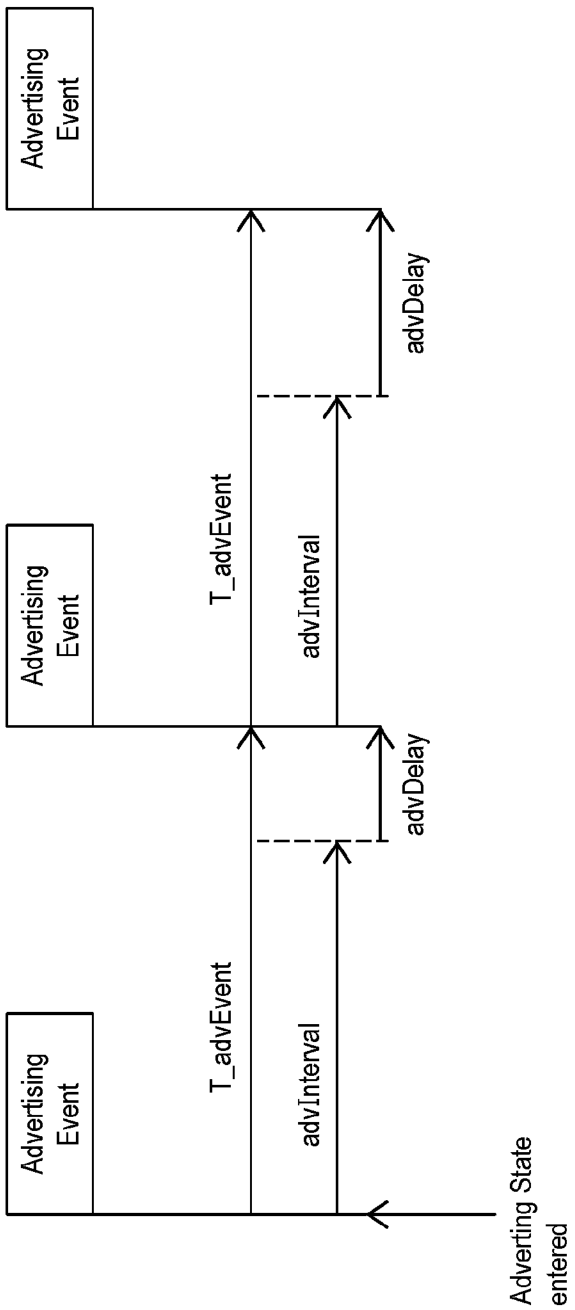

Advertising Event
Advertising Event
Advertising Event
T_advEvent
T_advEvent
advInterval
advInterval
advDelay
advDelay
Adverting State entered

FIGURE 10

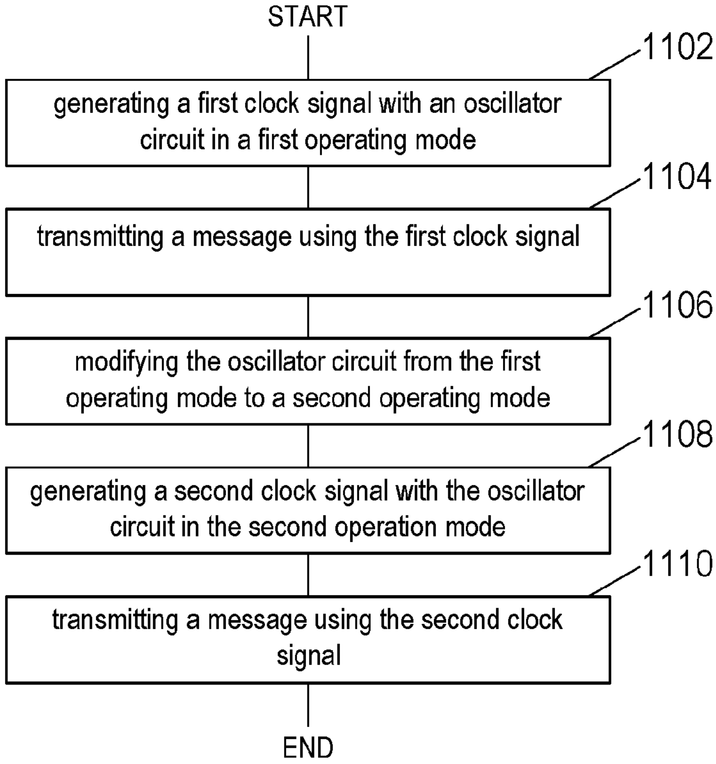

START
1102
generating a first clock signal with an oscillator circuit in a first operating mode
1104
transmitting a message using the first clock signal
1106
modifying the oscillator circuit from the first operating mode to a second operating mode
1108
generating a second clock signal with the oscillator circuit in the second operation mode
1110
transmitting a message using the second clock signal
END

FIGURE 11

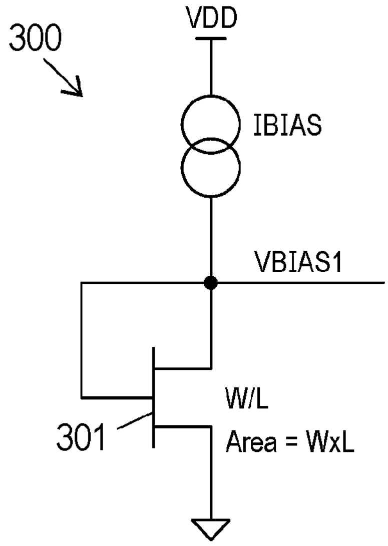


FIGURE 12A

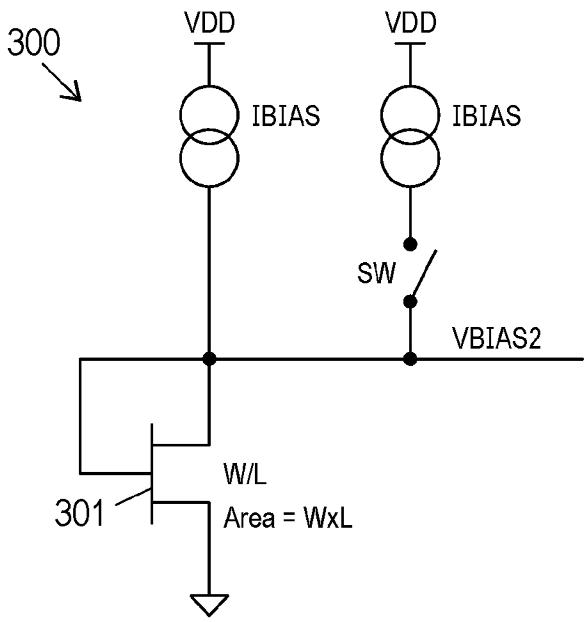


FIGURE 12B

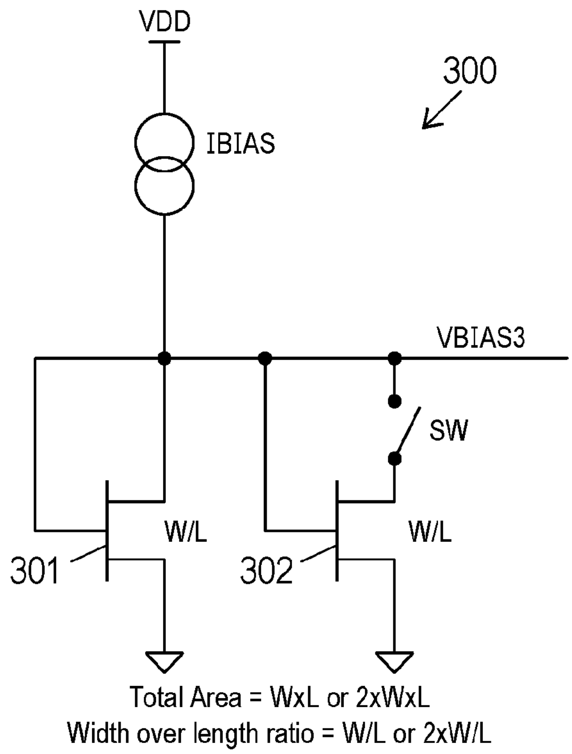
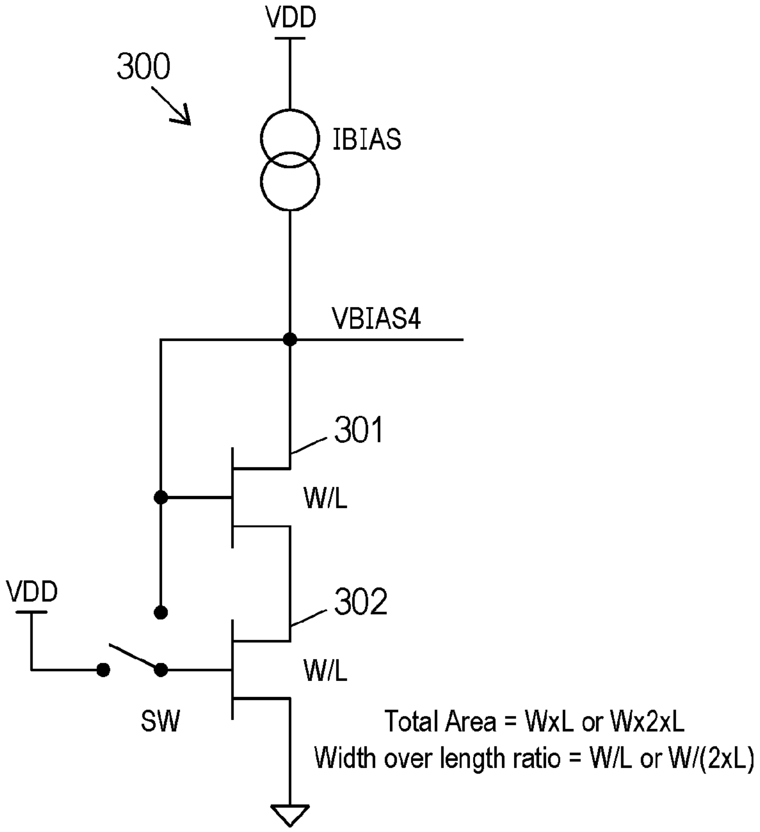

VDD
300
IBIAS
VBIAS3
SW
W/L
W/L
301
302
Total Area = WxL or 2xWxL
Width over length ratio = W/L or 2xW/L

FIGURE 12C



VDD
300
IBIAS
VBIAS4
301
W/L
VDD
302
W/L
SW
Total Area = WxL or Wx2xL
Width over length ratio = W/L or W/(2xL)

FIGURE 12D

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2022/050204

A. CLASSIFICATION OF SUBJECT MATTER
INV. H03B5/20
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H03B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2013/222069 A1 (PAIDIMARRI ARUN [US] ET AL) 29 August 2013 (2013-08-29)	1
A	paragraph [0021]; claim 9; figure 6	2

X	US 2019/079573 A1 (HANSON SCOTT MCLEAN [US] ET AL) 14 March 2019 (2019-03-14)	1,9,10
A	paragraph [0035] - paragraph [0107]	2

X	US 2009/085685 A1 (GUO XIAOLING [US] ET AL) 2 April 2009 (2009-04-02)	1,3-8
Y	paragraph [0127] - paragraph [0149];	6-8
A	figures 1, 17 paragraph [0055]	2

Y	WO 2009/108106 A1 (LEPTONRADIO AB [SE]; BILSTRUP URBAN [SE] ET AL.) 3 September 2009 (2009-09-03)	6-8
A	page 7, line 20 - line 38; figure 5	2

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

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 February 2023	10/05/2023

Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2022/050204

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2013222069 A1	29-08-2013	CN 103296968 A	11-09-2013
		US 2013222069 A1	29-08-2013
		US 2017155397 A1	01-06-2017
US 2019079573 A1	14-03-2019	CN 111316234 A	19-06-2020
		TW 201913290 A	01-04-2019
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		US 2019079573 A1	14-03-2019
		US 2019079574 A1	14-03-2019
		US 2019079575 A1	14-03-2019
		US 2020257352 A1	13-08-2020
		WO 2019055066 A1	21-03-2019
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WO 2009108106 A1	03-09-2009	EP 2260437 A1	15-12-2010
		WO 2009108106 A1	03-09-2009

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-10

   Device comprising RC oscillator operable in low power and high power mode and control circuit

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2. claims: 11-18

   Method of generating a first and a second clock and transmitting a message using both clocks

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3. claims: 19-22

   System comprising power management radio circuit, oscillator control circuit and wake circuit

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2022/050204

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims;; it is covered by claims Nos.:
1-10

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.