

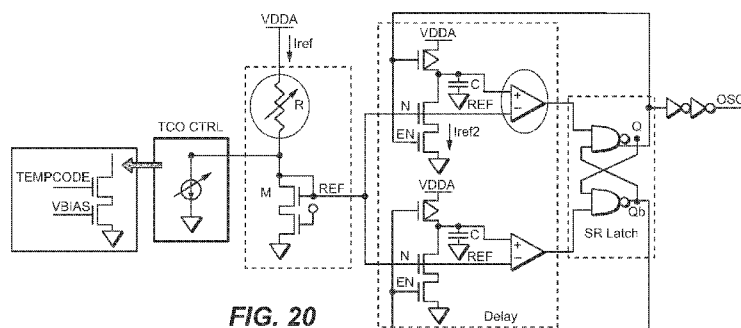


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(54) **Title:** METHODS AND APPARATUS FOR CLOCK OSCILLATOR TEMPERATURE COEFFICIENT TRIMMING**FIG. 20**

(57) **Abstract:** Apparatus and methods are provided for a temperature-compensated oscillator adapted to receive an input reference current. The apparatus and methods include or provide a temperature coefficient control circuit adapted to adjust the input reference current based on temperature information, wherein the temperature coefficient control circuit receives a first signal corresponding to the temperature information at a first signal node, and a second signal corresponding to a trimmed bias signal at a second signal node.

METHODS AND APPARATUS FOR CLOCK OSCILLATOR TEMPERATURE COEFFICIENT TRIMMING

FIELD OF THE INVENTION

[0001] The following pertains generally to the field of clock oscillator circuits.

BACKGROUND

[0002] Charge pumps use a switching process to provide a DC output voltage larger or lower than its DC input voltage. In general, a charge pump will have a capacitor coupled to switches between an input and an output. During one clock half cycle, the charging half cycle, the capacitor couples in parallel to the input so as to charge up to the input voltage. During a second clock cycle, the transfer half cycle, the charged capacitor couples in series with the input voltage so as to provide an output voltage twice the level of the input voltage. This process is illustrated in Figures 1a and 1b. In Figure 1a, the capacitor 5 is arranged in parallel with the input voltage V_{IN} to illustrate the charging half cycle. In Figure 1b, the charged capacitor 5 is arranged in series with the input voltage to illustrate the transfer half cycle. As seen in Figure 1b, the positive terminal of the charged capacitor 5 will thus be $2 * V_{IN}$ with respect to ground.

[0003] Charge pumps are used in many contexts. For example, they are used as peripheral circuits on flash and other non-volatile memories to generate many of the needed operating voltages, such as programming or erase voltages, from a lower power supply voltage. A number of charge pump designs, such as conventional Dickson-type pumps, are known in the art. But given the common reliance upon charge pumps, there is an ongoing need for improvements in pump design, particularly with respect to trying to save on current consumption.

SUMMARY

[0004] A clock generation circuit formed on an integrated circuit includes an oscillator connected to receive an internal reference voltage and generate from it a clock signal, where the frequency of the clock signal is dependent upon the level of the reference voltage, and an internal reference voltage generating circuit. The

internal reference voltage generating circuit includes a variable resistance element connected between a supply level and an internal node, where the internal reference voltage is taken from the internal node. The internal reference voltage generating circuit also includes a variable current source connected between the internal node and a first voltage level node and connected to receive a temperature code, wherein an amount of current flowing through the variable current source between the internal node and the first voltage level node is dependent upon the temperature code.

[0005] Various aspects, advantages, features and embodiments are included in the following description of exemplary examples thereof, which description should be taken in conjunction with the accompanying drawings. All patents, patent applications, articles, other publications, documents and things referenced herein are hereby incorporated herein by this reference in their entirety for all purposes. To the extent of any inconsistency or conflict in the definition or use of terms between any of the incorporated publications, documents or things and the present application, those of the present application shall prevail.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The various aspects and features may be better understood by examining the following figures, in which:

Figure 1a is a simplified circuit diagram of the charging half cycle in a generic charge pump;

Figure 1b is a simplified circuit diagram of the transfer half cycle in a generic charge pump;

Figure 2 illustrates the power efficiency of a charge pump system for various load levels;

Figure 3 is a top-level block diagram for a regulated charge pump;

Figures 4A-D look at the regulation of a charge pump using a fixed pump clock value;

Figures 5A-E look at the regulation of a charge pump using a pump clock value that can be varied continuously by the regulation circuitry based on feedback from the pump's output; and

Figures 6A and 6B respectively look at the clock generation blocks of Figures 4A and 5A in more detail.

Figure 6C is a more detailed version of Figure 6B.

Figure 7 looks an example similar to that described above with respect to Figure 6A for generating clock signals.

Figures 8A and 8B look at a Phase Lock Loop (PLL) and some of the basic parts in the exemplary embodiment here.

Figures 9A and 9B look at the Phase/Frequency Detector (PFD) functionality.

Figure 10 illustrates an exemplary embodiment for generating two additional clocks.

Figure 11 illustrates one maximum reference VCO embodiment.

Figure 12A shows VCTRL_REF sweep for reference PLL CLOCK and Figure 12B shows that for when VCTRL_REF is set to 50ns or 20MHz, changing VCTRL_X will further adjust (slowdown) the output clock frequency.

Figure 13 provides an Icc comparison.

Figure 14 illustrates a minimum reference VCO embodiment.

Figures 15-17 present some variations on the maximum reference VCO embodiment of Figure 11.

Figure 18 is an example of an uncompensated oscillator circuit.

Figure 19 illustrates the temperature behavior of the period of the circuit of Figure 18.

Figure 20 is an exemplary embodiment of a temperature compensated version of the circuit of Figure 18.

Figure 21 illustrates the temperature behavior and trimming of the circuit of Figure 20.

Figure 22 is an alternate embodiment of a temperature compensated version of the circuit of Figure 18.

Figure 23 illustrates the temperature behavior and trimming of the circuit of Figure 22.

DETAILED DESCRIPTION

[0007] Charge pumps are often operating in a low efficient region. To maintain small ripple, amplitude control can be used to match charge pump's drivability to its load;

and to handle the worst case loading condition, charge pumps are often operating in a low efficient region where pump's full strength drivability and its load are greatly mismatched. DC-DC converters such as charge pumps are typically optimized for power efficiency for the supplying large load currents. For example, on a non-volatile memory system this requirement is mainly related to AC capacitive current to needed charge up word lines. The efficiency of the system may drop to extremely low levels, less than 1% in some applications, after the capacitive load is charged up and the load current reduces to just what is needed due to leakage, as is the case during regulation to maintain word line voltages. Although performance requirements are based on the charging-up period, the system will typically be operating under regulation for a greater amount of time. To improve overall power efficiency, the power efficiency during regulation needs to be improved since it accounts for a significant amount of total operation time.

[0008] Figure 2 illustrates the efficiency of a charge pump system for various load levels. As shown, the DC-DC converter is optimized for power efficiency for the certain large load current levels, I_{AC} , mainly related to the main task for the pump, such as AC capacitive current to charge up word lines in a memory circuit example. Once this capacitance is charge up, the load current will reduce down to the leakage current, $I_{leakage}$, and the efficiency drops significantly, to possibly even below 1%. In the memory circuit example, $I_{leakage}$ is the level needed during regulation to maintain the word line voltage. To improve overall power efficiency for the system, power efficiency during regulation can be improved, since it accounts for a significant amount of total operation time.

[0009] The following presents techniques for maintaining a pump's output at a target value and pump strength, while power can be saved by dynamically adjust the clock frequency with full potential clock swing to match pump's driving strength to its DC load. A common application for charge pumps is in non-volatile memory circuits, such as those of the NAND flash or 3D type, that are often integrated into digital mobile devices where power consumption is one of the key features for performance. Outside of the actual memory array, charge pumps that generate supply voltage for peripheral circuits are significant power consumption blocks on the memory circuit. The pump systems presented below can help to maintain the output at a target value

and pump strength while power is saved by dynamically adjusting the clock frequency with full potential clock swing to match pump's driving strength to the load.

[0010] The following is primarily concerned with the regulation circuitry of charge pump systems rather than the details of the pump itself. For example, the pump can be based on a Dickson-type pump, voltage doublers, four-phase, and so on. More detail on various pumps and pump system within which the following concepts can be applied can be found in US patent application number 14/101,180 and references cited therein.

[0011] With respect to regulation, Figure 3 is a simplified top-level block diagram of a typical charge pump using an output voltage based regulation scheme. As shown in Figure 3, the pump 201 has as inputs a clock signal and a voltage V_{reg} and provides an output V_{out} . The clock generation circuit is not explicitly shown in Figure 3, although it may be considered part of the charge pump system in some embodiments or taken as an external input. The high (V_{dd}) and low (ground) connections are also not explicitly shown. The voltage V_{reg} is provided by the regulator 203, which has as inputs a reference voltage V_{ref} from an external voltage source and the output voltage V_{out} . The regulator block 203 generates feedback control signal V_{reg} such that the desired value of V_{out} can be obtained. The pump section 201 may have any of various designs for charge pumps, such as described in the various references cited above including charge doubler-type circuits with cross-coupled elements as well as the Dickson-type pumps described below for the exemplary embodiments. (A charge pump is typically taken to refer to both the pump portion 201 and the regulator 203, when a regulator is included, although in some usages "charge pump" refers to just the pump section 201. In the following, the terminology "charge pump system" will often be used to describe pump itself as well as any regulation or other peripheral elements.) The regulator block 203 typically compares the V_{ref} to the V_{out} value by using a voltage divider circuit. The voltage divider can be a resistive divider, a capacitive divider, or some combination (see, for example, US patent number 7,554,311).

[0012] Figures 4A-D look at a regulated charge pump system in more detail. The block diagram of Figure 4A includes pump 401 driving a load represented at 403.

The pump is driven by a clock signal CLK from a clock generator circuit CLKGEN 405 that is supplied through a clock driver. The clock driver CLKDRV includes the buffer 407 that is supplied at a level VSUP from the VCC level by the transistor 409. The pump 401 then receives the clock signal of amplitude VSUP. In this example the clock can be supplied with a fast (1x) and a slow (2x) period. The gate of the driver's transistor 409 is controlled by the regulation circuitry, with the output REG of the comparator 411 connected to the control gate of transistor 409. The inputs of the comparator 411 are connected to receive a reference level REF and feedback from the pump's output VOUT taken from a node of, in this example, a resistive voltage divider formed from R_0 413 and R_1 415.

[0013] The operation of the circuit of Figure 4A is described with respect to Figures 4B-D. In Figure 4B, ILOAD is an example of a DC load current profile; FAST is the current for the pump operating at maximum driving strength; and SLOW is the current for the pump at maximum driving strength, but at a 2 times slower clock frequency from FAST. In the arrangement of Figure 4A, the clock frequency is usually predetermined by considering worst case loading; however, in practice it is difficult to determine the exact timing and loading for the circuit due to the many different factors that enter in to load variation.

[0014] In Figure 4C, VCC is the external supply level; VSUP_FAST is the pump clock's supply level under regulation; and VSUP_SLOW is the pump clock's supply in regulation at a twice (2x) slower clock frequency relative to FAST. Matching pump's driving strength with the load is realized by a voltage drop to the clock supply, limiting the pump's strength. This results in large inefficiencies and power loss due to voltage drop, as illustrated by the gap between VCC and the VSUP levels.

[0015] Figure 4D illustrates the target pump output VOUT along with the realistic pump outputs VOUT_FAST and VOUT_SLOW, where the SLOW value is the pump output at a 2x slower clock frequency relative to FAST. In Figure 4D, both of VOUT_FAST and VOUT_SLOW rise to the target level and, mostly, stay there, except that at the highest load current VOUT_SLOW drops. This reflects that by not selecting the proper clock frequency (that is, in this example by selecting SLOW instead of FAST), VOUT can be out of the specification due to the pump's strength

being too weak. If it is instead selected to have proper clock frequency (here, FAST), the pump's ability and target load are can be greatly mismatched except for this peak current situation, resulting in a big I_{cc} penalty.

[0016] Figures 5A-E illustrate an exemplary embodiment of a charge pump system to help reduce this sort of inefficiency. Figure 5A is a schematic representation of a charge pump system, where similar elements are numbered similarly to those of Figure 4A (501 versus 401 for the charge pump, and so on). In Figure 5A, the regulation elements are now used to control the clock frequency, as illustrated the output REG of the comparator COMP 511 now being supplied to the clock generator block CLKGEN 505. This results in the clock period varying with the regulation level, as illustrated schematically in the output of CLKGEN 505 and also the clock driver 509 of the clock driver. (In this embodiment REG is also used to control the VSUP level provided the buffer 509 as in Figure 4A, but this is optional in the embodiment of Figure 5A.)

[0017] In Figure 5B ILOAD is again the DC Load current profile, which is the same example as in Figure 4b, and the line of larger squares is the pump maximum driving strength for the arrangement of Figure 5A. This closely matches with the load, being a little stronger. At bottom, in Figure 5E is the clock pump value CLK, showing how this varies with the requirements of the load.

[0018] Figure 5C illustrate the relation of the external supply level VCC and the pump clock supply level VSUP under regulation. There is a relatively minimal voltage drop from VCC to VSUP. This matching of the pump's driving strength to the DC load with minimal voltage drop can allow for significant improvements in efficiency and power savings.

[0019] In Figure 5D, the target VOUT level is compared to the level provided by the system of Figure 5A. By maintain the pump's output at the target value and dynamically adjusting the clock frequency with full potential clock swing, the system can match pump's driving strength to the DC load.

[0020] Figures 6A and 6B look at an exemplary embodiment of how the clock frequency can be dynamically adjusted based on the VOUT level for the regulation.

Figure 6A is an example for a CLKGEN block 405 as in Figure 4A. At right is an oscillator circuit 605 whose output frequency OSC depends on an input voltage level REF. Here REF is used as input to the detectors DT that provide the set/reset signals to the flip-flop SR, which in turn outputs OSC as well as the second inputs to the detectors. In this example, the oscillator is a relaxation RC oscillator, but ring oscillators or other circuits could be used. To provide the input voltage, a fixed resistance R_F 601 is connected in series with a diode connected transistor 603 between and ground. The input voltage REF is taken from the node between resistance R_F 601 and diode 603. As REF is fixed, the generated clock frequency OSC is fixed.

[0021] Figure 6B gives an example of a CLKGEN block 505 such as could be used in Figure 5A. Instead of a fixed REF value, REF is adjusted by the regulation circuitry to generate a clock frequency to match the pump's ability to drive the DC load it sees. The oscillator 707 is again taken as a relaxation RC oscillator, but ring oscillators or other circuits could be used. The divider circuit used to provide REF now uses the regulation signal REG based on feedback from VOUT to determine the REF level and, hence, the OSC frequency. The node from REF is taken in again connected to ground (or, more generally, the low voltage level) through the diode connected transistor 705. In other embodiments, a resistor could be used. Between VCC and the REF, a variable resistance whose value depends on REG is now included. Here this is implemented by the PMOS 701 whose gate is connected to receive the regulation signal. In this embodiment, a fixed resistance R_F 703 is in series with the variable element. For references, Figure 6C is a more detailed version of Figure 6B that includes the capacitances and other elements in more detail. (In Figure 6C, the resistance R_F 703' is illustrated as variable, indicating that it, or at least a portion of it, is adjustable in order to set the RC constant of the circuit; however, as far as the REG value, this is still a fixed value and does not vary with the regulation level.) Other embodiments could arrange the elements of divider supplying REF differently and use other element, such as an NMOS instead of the PMOS, for example. In this way, the clock frequency CLK for the pump can track the requirements of the load as described in Figures 5B-D.

[0022] For any of the variations, the arrangement described above can increase power savings and reduce current consumption of the charge pump block. By

adjusting the pump clock frequency to regulate pump operations, the pump's maximum driving strength with full clock swing is matched to the pump's DC load for higher efficiency.

MULTI-CLOCK GENERATION THROUGH PLL REFERENCE

[0023] In flash memory, power consumption is a key element for performance. To reduce power consumption, more efficient charge pumps and usage are required. As a result, charge pumps require their own clock frequency so that their output capability can match their load. With many different supplies (charge pumps), many clock generators are required.

[0024] The techniques presented here for clock generation can be implemented as peripheral elements on integrated circuits for many applications. In particular, such clock circuits are often part of a non-volatile memory circuit, such as flash NAND memory and non-volatile memories having a 3D array type structure. More detail on NAND memory devices can be found in US patent and publication numbers 20080158969; 5,570,315; 5,903,495; and 6,046,935, for example. More detail on non-volatile memory having a 3D array structure can be found in US patent publication numbers: 2012-0147649; 2014-0192595; and 2014-0179068, for example.

[0025] With respect to the memory devices, semiconductor memory devices include volatile memory devices, such as dynamic random access memory ("DRAM") or static random access memory ("SRAM") devices, non-volatile memory devices, such as resistive random access memory ("ReRAM"), electrically erasable programmable read only memory ("EEPROM"), flash memory (which can also be considered a subset of EEPROM), ferroelectric random access memory ("FRAM"), and magnetoresistive random access memory ("MRAM"), and other semiconductor elements capable of storing information. Each type of memory device may have different configurations. For example, flash memory devices may be configured in a NAND or a NOR configuration.

[0026] The memory devices can be formed from passive and/or active elements, in any combinations. By way of non-limiting example, passive semiconductor memory elements include ReRAM device elements, which in some embodiments include a

resistivity switching storage element, such as an anti-fuse, phase change material, etc., and optionally a steering element, such as a diode, *etc.* Further by way of non-limiting example, active semiconductor memory elements include EEPROM and flash memory device elements, which in some embodiments include elements containing a charge storage region, such as a floating gate, conductive nanoparticles, or a charge storage dielectric material.

[0027] Multiple memory elements may be configured so that they are connected in series or so that each element is individually accessible. By way of non-limiting example, flash memory devices in a NAND configuration (NAND memory) typically contain memory elements connected in series. A NAND memory array may be configured so that the array is composed of multiple strings of memory in which a string is composed of multiple memory elements sharing a single bit line and accessed as a group. Alternatively, memory elements may be configured so that each element is individually accessible, *e.g.*, a NOR memory array. NAND and NOR memory configurations are exemplary, and memory elements may be otherwise configured.

[0028] The semiconductor memory elements located within and/or over a substrate may be arranged in two or three dimensions, such as a two dimensional memory structure or a three dimensional memory structure.

[0029] In a two dimensional memory structure, the semiconductor memory elements are arranged in a single plane or a single memory device level. Typically, in a two dimensional memory structure, memory elements are arranged in a plane (*e.g.*, in an x-z direction plane) which extends substantially parallel to a major surface of a substrate that supports the memory elements. The substrate may be a wafer over or in which the layer of the memory elements are formed or it may be a carrier substrate which is attached to the memory elements after they are formed. As a non-limiting example, the substrate may include a semiconductor such as silicon.

[0030] The memory elements may be arranged in the single memory device level in an ordered array, such as in a plurality of rows and/or columns. However, the memory elements may be arrayed in non-regular or non-orthogonal configurations. The memory elements may each have two or more electrodes or contact lines, such as bit lines and word lines.

[0031] A three dimensional memory array is arranged so that memory elements occupy multiple planes or multiple memory device levels, thereby forming a structure in three dimensions (*i.e.*, in the x, y and z directions, where the y direction is substantially perpendicular and the x and z directions are substantially parallel to the major surface of the substrate).

[0032] As a non-limiting example, a three dimensional memory structure may be vertically arranged as a stack of multiple two dimensional memory device levels. As another non-limiting example, a three dimensional memory array may be arranged as multiple vertical columns (*e.g.*, columns extending substantially perpendicular to the major surface of the substrate, *i.e.*, in the y direction) with each column having multiple memory elements in each column. The columns may be arranged in a two dimensional configuration, *e.g.*, in an x-z plane, resulting in a three dimensional arrangement of memory elements with elements on multiple vertically stacked memory planes. Other configurations of memory elements in three dimensions can also constitute a three dimensional memory array.

[0033] By way of non-limiting example, in a three dimensional NAND memory array, the memory elements may be coupled together to form a NAND string within a single horizontal (*e.g.*, x-z) memory device levels. Alternatively, the memory elements may be coupled together to form a vertical NAND string that traverses across multiple horizontal memory device levels. Other three dimensional configurations can be envisioned wherein some NAND strings contain memory elements in a single memory level while other strings contain memory elements which span through multiple memory levels. Three dimensional memory arrays may also be designed in a NOR configuration and in a ReRAM configuration.

[0034] Typically, in a monolithic three dimensional memory array, one or more memory device levels are formed above a *single* substrate. Optionally, the monolithic three dimensional memory array may also have one or more memory layers at least partially within the single substrate. As a non-limiting example, the substrate may include a semiconductor such as silicon. In a monolithic three dimensional array, the layers constituting each memory device level of the array are typically formed on the layers of the underlying memory device levels of the array. However, layers of

adjacent memory device levels of a monolithic three dimensional memory array may be shared or have intervening layers between memory device levels.

[0035] Then again, two dimensional arrays may be formed separately and then packaged together to form a non-monolithic memory device having multiple layers of memory. For example, non-monolithic stacked memories can be constructed by forming memory levels on separate substrates and then stacking the memory levels atop each other. The substrates may be thinned or removed from the memory device levels before stacking, but as the memory device levels are initially formed over separate substrates, the resulting memory arrays are not monolithic three dimensional memory arrays. Further, multiple two dimensional memory arrays or three dimensional memory arrays (monolithic or non-monolithic) may be formed on separate chips and then packaged together to form a stacked-chip memory device.

[0036] Associated circuitry is typically required for operation of the memory elements and for communication with the memory elements. As non-limiting examples, memory devices may have circuitry used for controlling and driving memory elements to accomplish functions such as programming and reading. This associated circuitry may be on the same substrate as the memory elements and/or on a separate substrate. For example, a controller for memory read-write operations may be located on a separate controller chip and/or on the same substrate as the memory elements.

[0037] It will be recognized that the following is not limited to the two dimensional and three dimensional exemplary structures described but cover all relevant memory structures within the spirit and scope as described herein

[0038] One way to provide a number of separate clock signals, whether on memory devices or other circuits, is where each clock is generated by a separate trimmable RC-oscillator, which requires more area and I_{cc} . In this section, techniques are instead presented for generating a reference clock through phase lock loop (PLL) at a certain frequency, and then using a voltage control (VCTRL) as a reference to set as the maximum or minimum of other derived frequencies. It can also be used, with other controls or inputs, to generate many different clock frequencies that can be trimmed to be a fixed value or adjustable on the fly. Since the VCO can

be formed by use of a few inverters (ring oscillator), I_{cc} and area can be reduced relative to having multiple separately trimmable RC-oscillators.

[0039] Figure 7 looks an example similar to that described above with respect to Figures 6A-C for generating clock signals in a NAND flash system or 3D type non-volatile memory system. There will typically be many clock generators due to dedicated clocks for charge pumps to obtain high efficiency (reduced I_{cc}) across different loading conditions, for other pumps, logics, and so on. Figure 7 illustrates this for an example where one clock (CLK) is needed for various logic, pump and other circuits, and two individually regulated pumps (A, B) receive corresponding clock signals drive two different loads. Each of these clock generation circuits would be distinct, such as shown at the left of the figure or in more details in Figures 6A-C. The multiple clock generation circuits results in a larger area and higher current consumption (I_{cc}).

[0040] To reduce area requirements, current consumption, or both, this section presents techniques for generating a reference clock through phase lock loop (PLL) at a certain frequency, and then using one or more voltage controls (VCTRL) as a reference to set the maximum or minimum of other derived frequencies.. This can be used, with other controls or inputs, to generate many different clock frequencies by use of voltage controlled oscillators (VCOs): trimmed to be fixed or adjustable on the fly, such as for the regulation of charge pumps, for example. Since a VCO can be formed of a few inverters (ring oscillator), I_{cc} and area can be reduced. Note that although the focus of PLLs is traditionally for accuracy (low noise) and high speed, here the focus is more on reducing layout area and I_{cc} , with the frequencies involved being relatively lower than common PLL applications.

[0041] Figures 8A and 8B look at a Phase Lock Loop (PLL) and some of the basic parts in the exemplary embodiment here. An input reference clock is received at a phase/frequency detector (PFD) 801 along with a clock (CLK_REF_OUT) derived from the output clock (CLK_OUT). Based these two values, PFD 801 generates UP and DOWN that are supplied to a charge pump 803, whose output passes through a low pass filter 805 to provide the control voltage VCTRL to regulate the oscillator 807 to generate the output clock CLK_OUT. (The shown charge pump

in the PLL, between the FPD and the low pass filter is here used to function more as a switch than a high voltage charge pump.) Figure 8B is an exemplary embodiment for a VCO, illustrating how VCTRL is used to control the current I_{ref} that is mirrored to control CLK_OUT. CLK_OUT then is fed back through a frequency divider 809 and back to PFD 801. For example, consider the example of a given CLK_REF=200ns, frequency divider with $N=4$, and target at CLK_OUT=50ns. Once enabled, the PFD 801 will adjust VCTRL such that CLK_OUT will reach target of 50ns and CLK_REF_OUT will be in phase with CLK_REF at 200ns. The circuit will eventually lock in the target frequency and VCTRL becomes a stable voltage for CLK_OUT with given CLK_REF. VCTRL maintains the current (I_{ref}) that will mirror to control supply of the ring oscillator, where (see Figure 8B) $I_{ref} = I_{res} = V_R / R$.

[0042] Figures 9A and 9B look at the Phase/Frequency Detector (PFD) functionality. This will detect the edge of Reference clock (CLK_REF in Figure 8A) and PLL output (CLK_REF_OUT in Figure 8A): if REF is faster, the pump charges into VCTRL to increase the PLL output frequency; and if REF is slower, the pump discharges charge from VCTRL to decrease PLL output frequency. As shown in Figure 9A, REF is faster, so that the UP signal is high until the PLL Out edge is detected, and VCTRL is increased to increase the PLL frequency. In Figure 9B, REF is slower, so the DOWN signal is high until the REF edge is detected, and VCTRL is decreased to decrease the PLL frequency.

[0043] Figure 10 illustrates an exemplary embodiment for generating two additional clocks. The elements of Figure 8A are repeated and similarly numbered, with a reference clock generator CLKGEN 800 also shown. Additional clock signals can then be generated in addition oscillators, where here two are shown with VCO 811 generating CLK_A and VCO 821 generating CLK_B. The additional clock signals are trimmable and then can also be controlled on the fly, such as based on feedback from a charge pump to be used for regulation purposes. Based on the established VCTRL_REF with known CLK_OUT frequency, the other frequencies can be derived with a couple of parameters. VCTRL_REF now can be used as the reference point. A separate control (for example TRIM_A<M:1>) can be used to adjust or fine

tune the derived frequency. A separate VCTRL (for example VCTRL_A which could be feedback from a pump) can be used to modulate the frequency on the fly.

[0044] By generating a reference clock through the phase locked loop (PLL) at a certain frequency, the voltage control (VCTRL) is known and be used as a reference to set as the maximum or minimum of other derived frequencies. It can also be used, with other controls or inputs, to generate many other needed different clock frequencies in additional VCO circuits, that can trimmed to be a fixed value or adjustable on the fly. Since a VCO can be made from few inverters (as a ring oscillator), total current (I_{cc}) and area needed for generating these multiple clocks can be reduced. There are many different configurations for either maximum reference or minimum reference VCO embodiments.

[0045] Figure 11 illustrates one embodiment for maximum reference VCO embodiment. Here the basic elements are again arranged as in the exemplary embodiment of Figure 8B, although other arrangements for the oscillators. Ignoring the far left leg (with transistor 905), the circuit is as in Figure 8B with the output clock (CLK_X) determined by the VCTRL_REF level from the PLL on the gate of 901. With a given VCTRL_REF, by adjusting the resistor R 903 by TRIM_X<M:1>, I_{res} and I_{ref} will change. It will affect the VSUP_COM/VSRC_COM and adjust the oscillator frequency. If it is also desired to change the frequency on fly, such as using feedback from regulation circuitry of a charge pump, this can be done by including the left leg with the (P or N type) transistor 905. By adjusting VCTRL_X to the gate of 905, the equation is now changed to $I_{res} = I_{ref} + I_{vctrl}$, affecting the VSUP_COM/VSRC_COM ratio and adjusting the oscillator frequency so that the VCTRL_X can be used to regulate the CLK value downward from a maximum as set by VCTRL_REF and the trim value.

[0046] Figures 12A and 12B looked at CLK control for this arrangement for a particular example. Figure 12A shows VCTRL_REF sweep for reference PLL CLOCK and Figure 12B shows that for when VCTRL_REF is set to 50ns or 20MHz, changing VCTRL_X will further adjust (slow down from the maximum) the output clock frequency of the secondary oscillator.

[0047] Figure 13 provides an I_{cc} comparison for a particular implementation. In a system with at least 2 clock frequencies (for example, 50ns and 80ns), the embodiments of this section can save at least 25% I_{cc} . As the unit of clock frequency increases, the saving will be realized much further since each additional clock will consume maximum of 16uA.

[0048] Whereas Figure 11 presented a maximum reference VCO embodiment, Figure 14 illustrates a minimum reference VCO embodiment. Aside from the far left leg, with transistor 1005, the basic VCO is the same as in Figure 8A or (again without the left leg) Figure 11. With a given VCTRL_REF to the gate of 1001, by adjusting the resistor R 1003 by TRIM_X<M:1>, I_{res} and I_{ref} will change, affect the VSUP_COM/VSRC_COM and adjust the oscillator frequency as for Figure 11. The left leg now drains off current from above transistor 1001; By adjusting VCTRL_X on the gate of (P or N type) transistor 1005, the current equation is now changed for min frequency to $I_{ref} = I_{res} + I_{vctrl}$. This will affect the VSUP_COM/VSRC_COM ratio and adjust the oscillator frequency on the fly, so that the VCTRL_X can be used to regulate the CLK value upward from a minimum as set by VCTRL_REF and the trim value.

[0049] Figures 15-17 present some variations on the maximum reference VCO embodiment of Figure 11. In each of these, the VCTRL_X controls the transistor to provide additional current at various legs of the oscillator to add current and increase the output frequency. Similar variations on Figure 14, but instead using VCTRL_X to drain off current, can also be implemented for the minimum reference VCO embodiments.

TEMPERATURE COEFFICIENT TRIMMING

[0050] It has been noted that clock generating circuits, such as those discussed above with respect Figures 6A-C, 8B, 11 or 14-17, may exhibit a temperature dependence in their frequencies. This can in turn introduce a temperature dependent behavior in circuits using the clock signals. For example, in the non-volatile memory applications discussed above, this temperature dependence may exhibit itself in programming times, introducing a noticeable increase in programming times at, say, 85C relative to that at 25C. To compensate for this effect, this section considers the

use temperature information and a bias source dependent upon this temperature information, which can be trimmed at die-sort to provide a clock oscillator with reduced temperature dependence.

[0051] Figure 18 is similar to Figure 6B, but without the transistor 701' to simplify the discussion of this section. (Although the following discussion is based on this particular exemplary circuit, it can be extended to the various embodiments presented above.) The OSC frequency is largely determined by I_{ref} through resistor the R, which effectively controls the discharge rate of the capacitor C, based on $I_{ref2} = N/M * I_{ref}$. Due to the resistance's variation and transistor variation from temperature, the OSC frequency has a positive temperature coefficient (TCO). This is illustrated schematically in Figure 19.

[0052] By adjusting the ration of I_{ref}/I_{ref2} through use of a current sink or source with temperature information (tempcode), compensation can be made for the temperature dependent behavior. An exemplary embodiment is shown in Figure 20. In the exemplary embodiment, a current sink is connected between the internal reference voltage node REF and ground, where the amount of current is a non-decreasing function of the tempcode value for the a temperature circuit that can also be formed on the integrated circuit. (If, instead of the period increasing with temperature as shown in Figure 19, the period decreased, a current source connected between the supply level and the REF node could be used, as discussed below with respect to Figures 22 and 23.) At left, Figure 20 illustrates an exemplary embodiment for the current sink where a first transistor whose gate is connected to receive the tempcode values is connected between the REF node and, through a second transistor, to ground. The gate voltage of the second transistor, VBIAS, can be set during trimming. This arrangement effectively applies a counteracting temperature coefficient to the OSC frequency which can compensate to reduce the temperature dependence of OSC. The result is illustrated schematically in Figure 21, where the trim value VBIAS and the tempcode provide a flat period over the operating range.

[0053] The VBIAS level and tempcode can either be digital or analog depending on the implementation. For example, memory circuits may already have a digital temperature sensing element which can also be used to supply the tempcode value

here. The number of bits can be based on the range of temperatures to be covered and the level of accuracy desired, such as having 5 bits for the -40C to 125C range illustrated in Figure 21.

[0054] In an exemplary trimming flow, at a first temperature (such as 85C in Figure 21) the tempcode can be acquired from a temperature sensor initially, or hardwired based upon characterization values. The oscillator frequency is then trimmed to a target value. As a second temperature, say -30C, the tempcode can then also be acquired from the temperature sensor or hardwired based upon characterization values. The trimming to the target value can be set based on, for example, a 3 bit trim value for VBIAS.

[0055] As noted above, if, instead of the period increasing with temperature as shown in Figure 19, the period decreased, a current source connected between the supply level and the REF node could be used. Figure 22 illustrates an alternate embodiment where, in addition to the variable current sink connected between the REF node and ground, a current source is also included between a supply level (here the same supply level as for the oscillator) and the REF node. This combined embodiment allows a combined treatment for when the period increases or decreases with temperature. Figure 23 is similar to Figure 21, but illustrates the temperature behavior and trimming of the circuit of Figure 22 rather than Figure 20.

Conclusion

[0056] The foregoing detailed description has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the above to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The described embodiments were chosen in order to explain the principles involved and its practical application, to thereby enable others to best utilize the various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope be defined by the claims appended hereto.

IT IS CLAIMED:

1. A clock generation circuit formed on an integrated circuit, comprising:
 - an oscillator connected to receive an internal reference voltage and generate therefrom a clock signal, wherein the frequency of the clock signal is dependent upon the level of the internal reference voltage; and
 - an internal reference voltage generating circuit including:
 - a variable resistance element connected between a supply level and an internal node, wherein the internal reference voltage is taken from the internal node; and
 - a variable current source connected between the internal node and a first voltage level node and connected to receive a temperature code, wherein an amount of current flowing through the variable current source between the internal node and the first voltage level node is dependent upon the temperature code.
2. The clock generation circuit of claim 1, wherein first voltage level node is connected to the supply level and the amount of current flowing from the first voltage level node to the internal node is a non-decreasing function of the temperature code.
3. The clock generation circuit of claim 1, wherein first voltage level node is connected ground and the amount of current flowing from the internal node first to the voltage level node is a non-decreasing function of the temperature code.
4. The clock generation circuit of claim 1, wherein the internal reference voltage generating circuit further includes:
 - a diode connected between the internal node and ground.
5. The clock generation circuit of claim 1, wherein the internal reference voltage generating circuit further includes:
 - a first fixed resistance connected between the internal node and ground.
6. The clock generation circuit of claim 1, wherein the oscillator is a relaxation oscillator circuit.

7. The clock generation circuit of claim 1, wherein the oscillator is a ring oscillator circuit.

8. The clock generation circuit of claim 1, wherein the internal reference voltage generating circuit further includes:

a diode connected between the internal node and ground.

9. The clock generation circuit of claim 1, wherein the variable current source includes a first transistor connected between the internal node and the first voltage level node whose control gate is connected to receive the temperature code.

10. The clock generation circuit of claim 9, wherein the first transistor is connected to the first voltage level node through a second transistor having a control gate set to a trimmable bias level.

11. The clock generation circuit of claim 1, wherein the temperature code is a multi-bit digital value.

12. The clock generation circuit of claim 1, wherein the temperature code is an analog value.

13. The clock generation circuit of claim 1, wherein the integrated circuit further includes temperature sensing circuit to provide the temperature code.

14. The clock generation circuit of claim 1, wherein the integrated circuit is a non-volatile memory circuit.

15. The clock generation circuit of claim 14, wherein the memory circuit is a monolithic three-dimensional semiconductor memory device where the memory cells are arranged in multiple physical levels above a silicon substrate and comprise a charge storage medium.

16. A method of generating a clock signal in a clock generation circuit formed on an integrated circuit, the clock generating circuit including an oscillator and an internal reference voltage generating circuit that includes a variable resistance element connected between a supply level and an internal node and a variable current source connected between the internal node and a first voltage level node, the method comprising:

receiving a temperature code at the variable current source;

generating a current flowing through the variable current source between the internal node and the first voltage level node, where the amount the current is dependent upon the temperature code;

providing an internal reference voltage from the internal node;

receiving the internal reference voltage at the oscillator; and

generating a clock signal by the oscillator from the internal reference voltage, wherein the frequency of the clock signal is dependent upon the level of the internal reference voltage

17. The method of claim 16, wherein first voltage level node is connected to the supply level and the amount of current flowing from the first voltage level node to the internal node is a non-decreasing function of the temperature code.

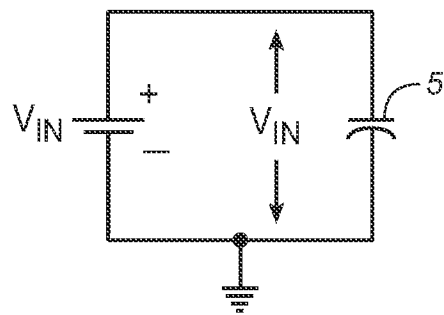
18. The method of claim 16, wherein first voltage level node is connected to ground and the amount of current flowing from the internal node first to the voltage level node is a non-decreasing function of the temperature code.

19. The method of claim 16, wherein the oscillator is a relaxation oscillator circuit.

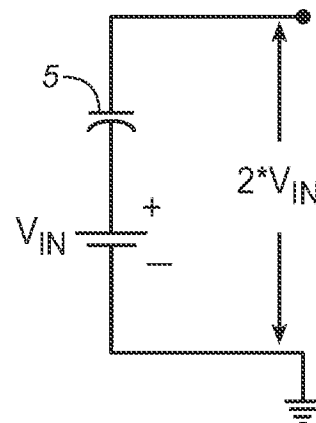
20. The method of claim 16, wherein the oscillator is a ring oscillator circuit.

21. The method of claim 16, wherein the memory circuit is a monolithic three-dimensional semiconductor memory device where the memory cells are arranged in multiple physical levels above a silicon substrate and comprise a charge storage medium.

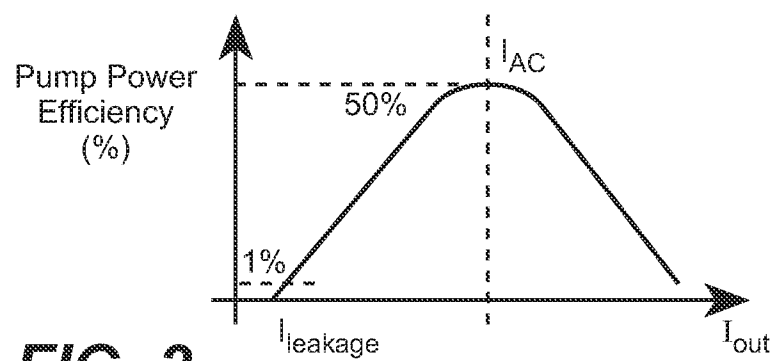
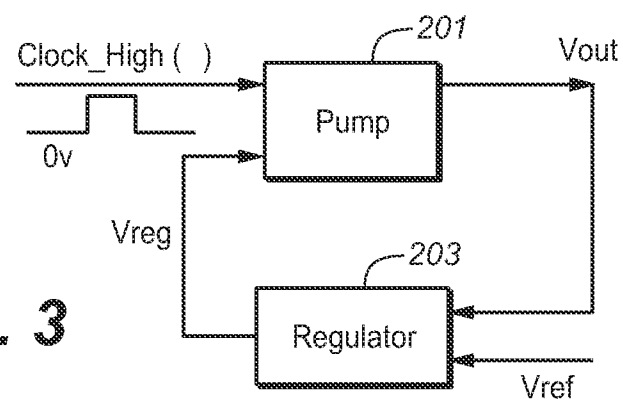
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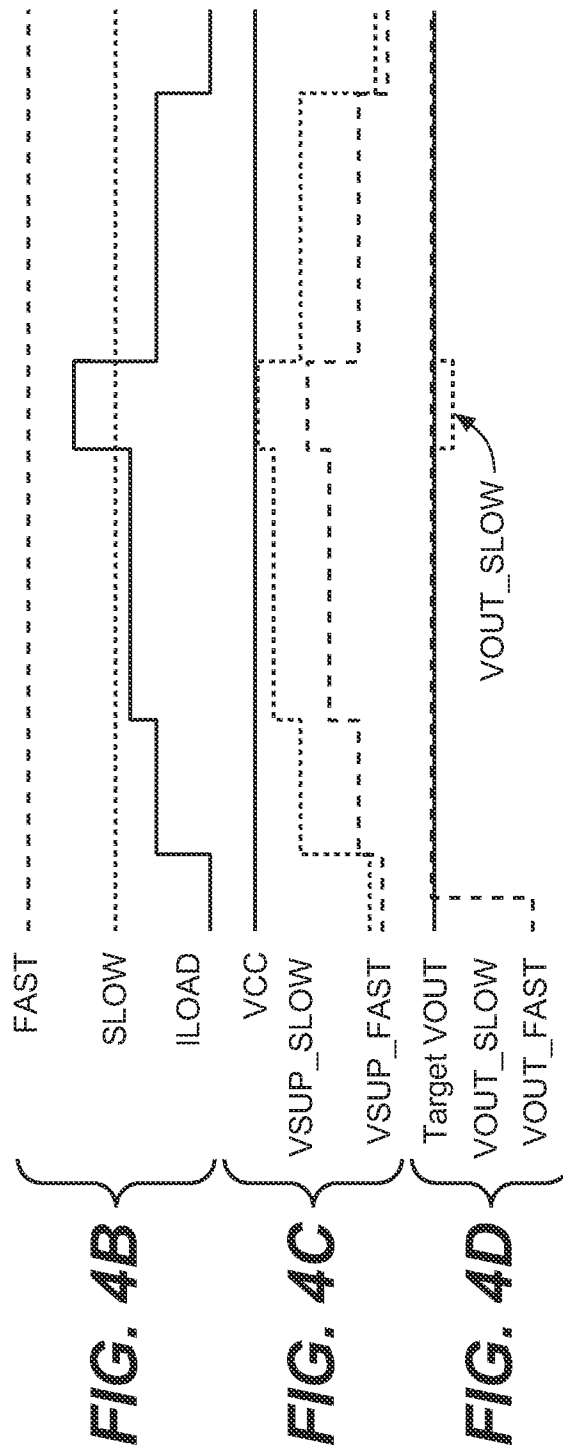
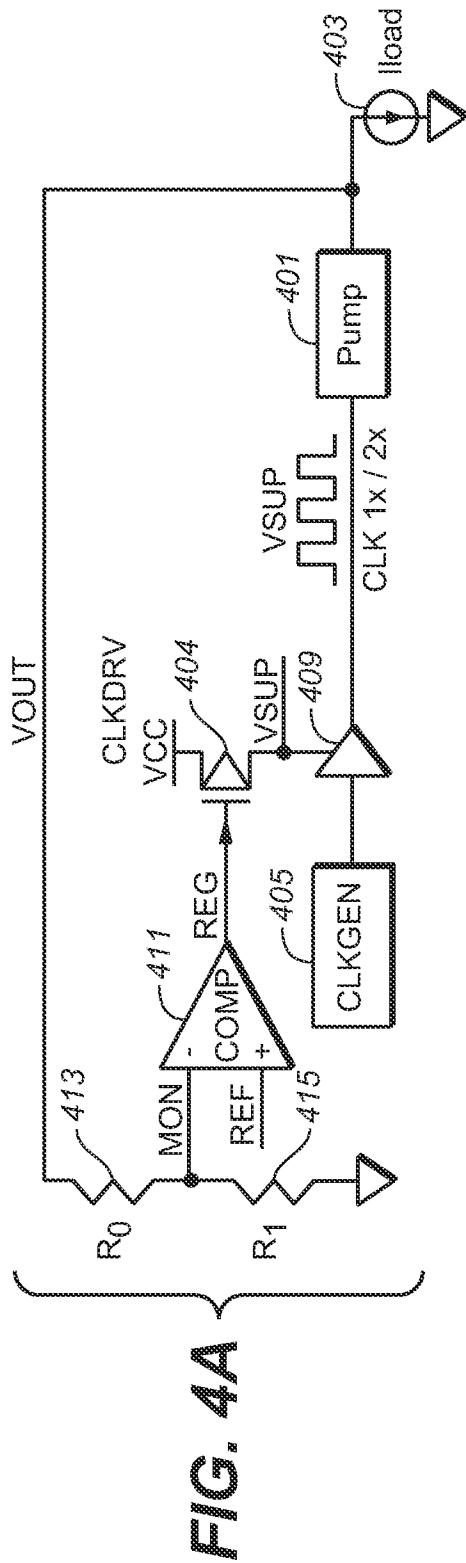


Charging Half Cycle

FIG. 1A

Transfer Half Cycle

FIG. 1B**FIG. 2****FIG. 3**



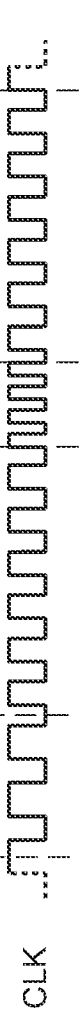
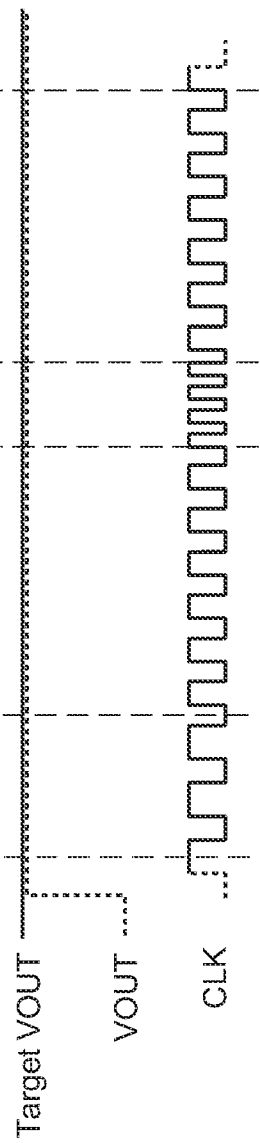
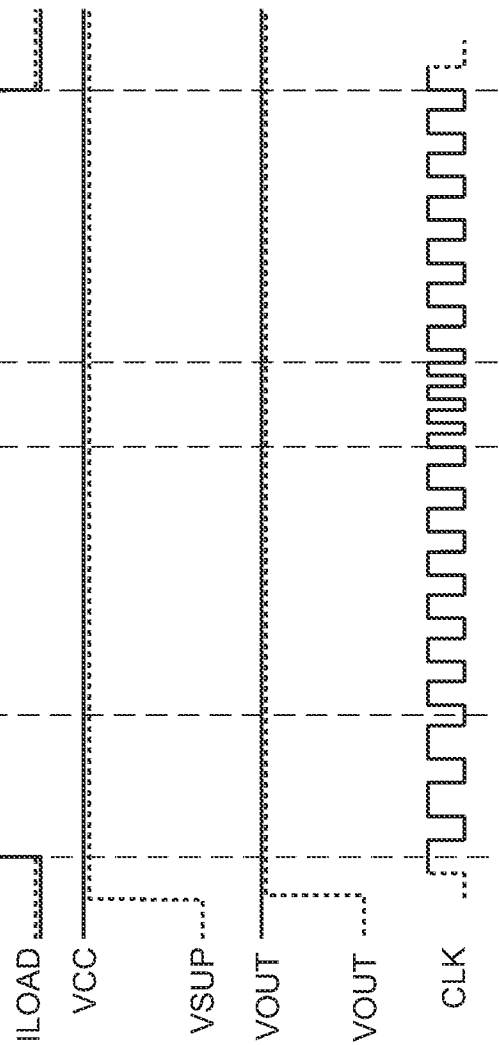
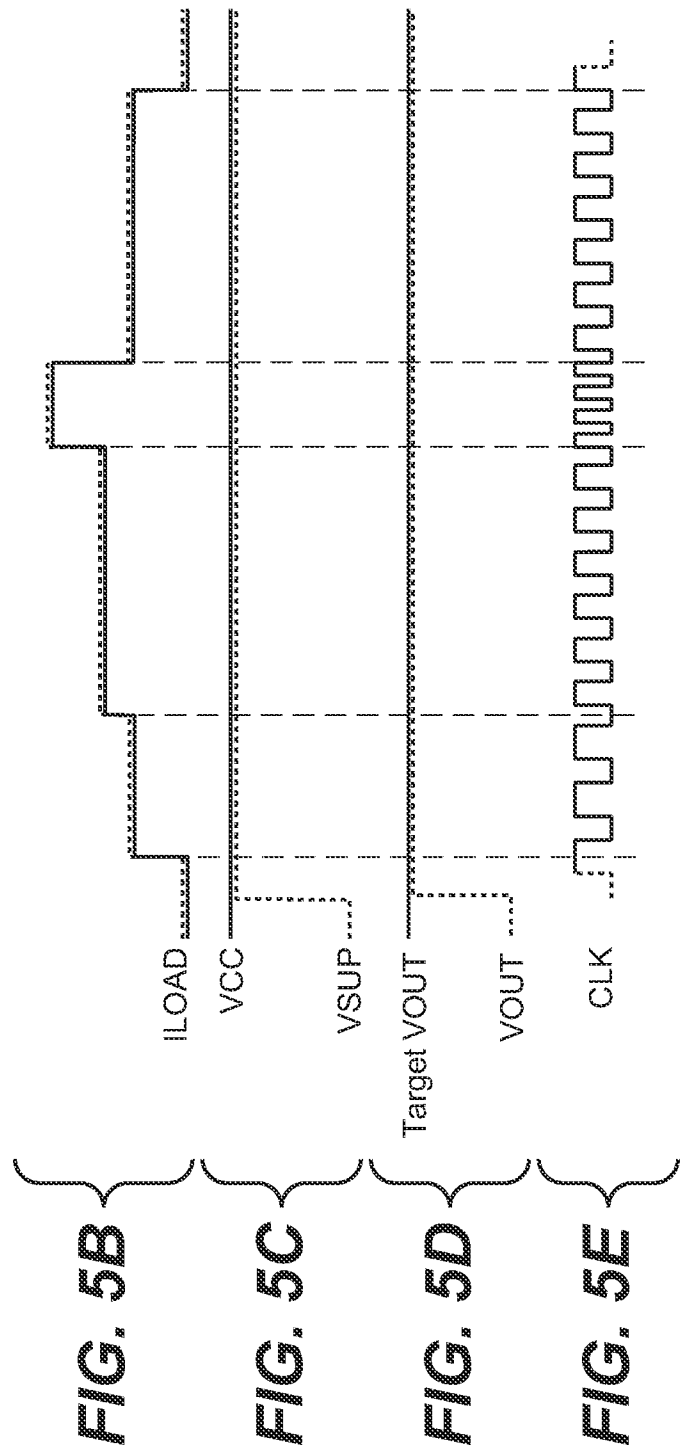
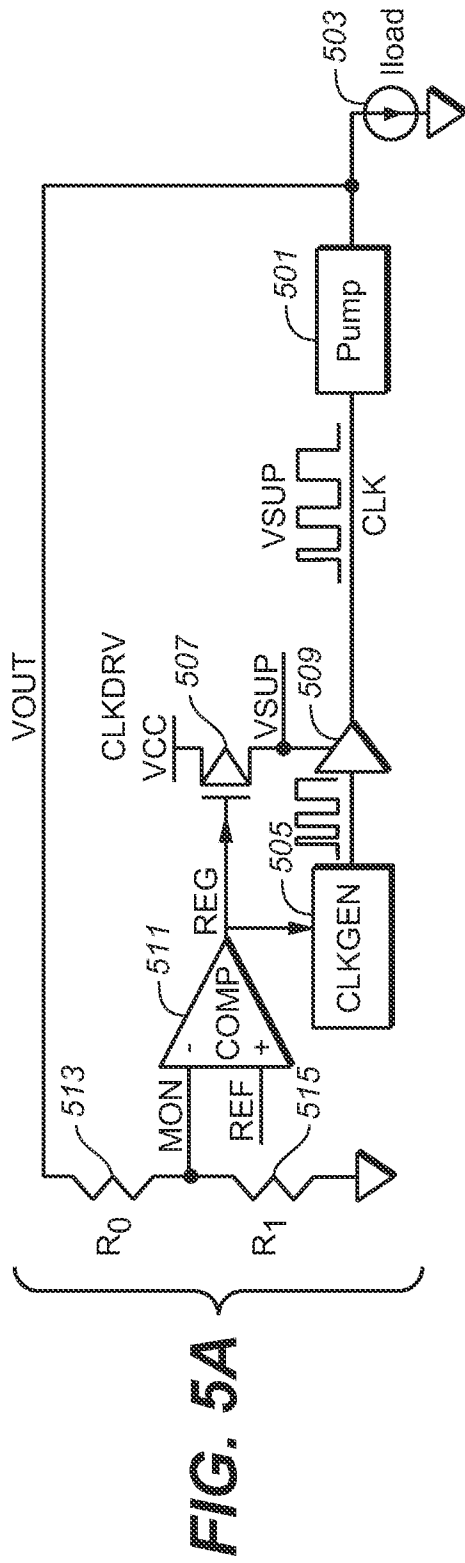


FIG. 6A

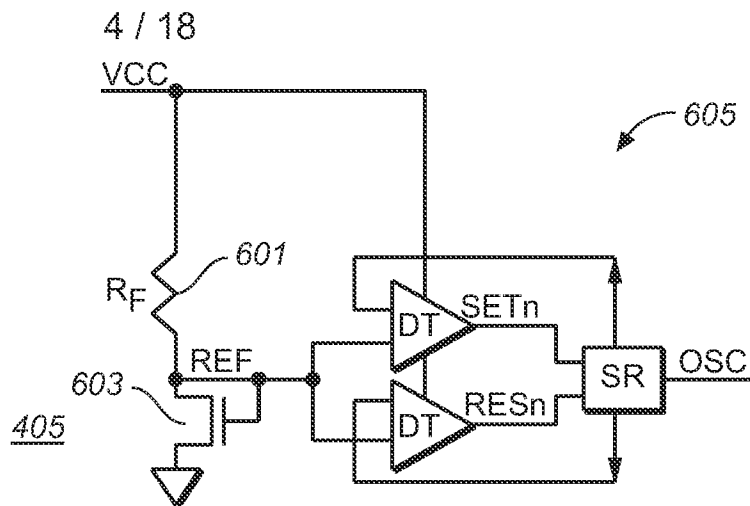


FIG. 6B

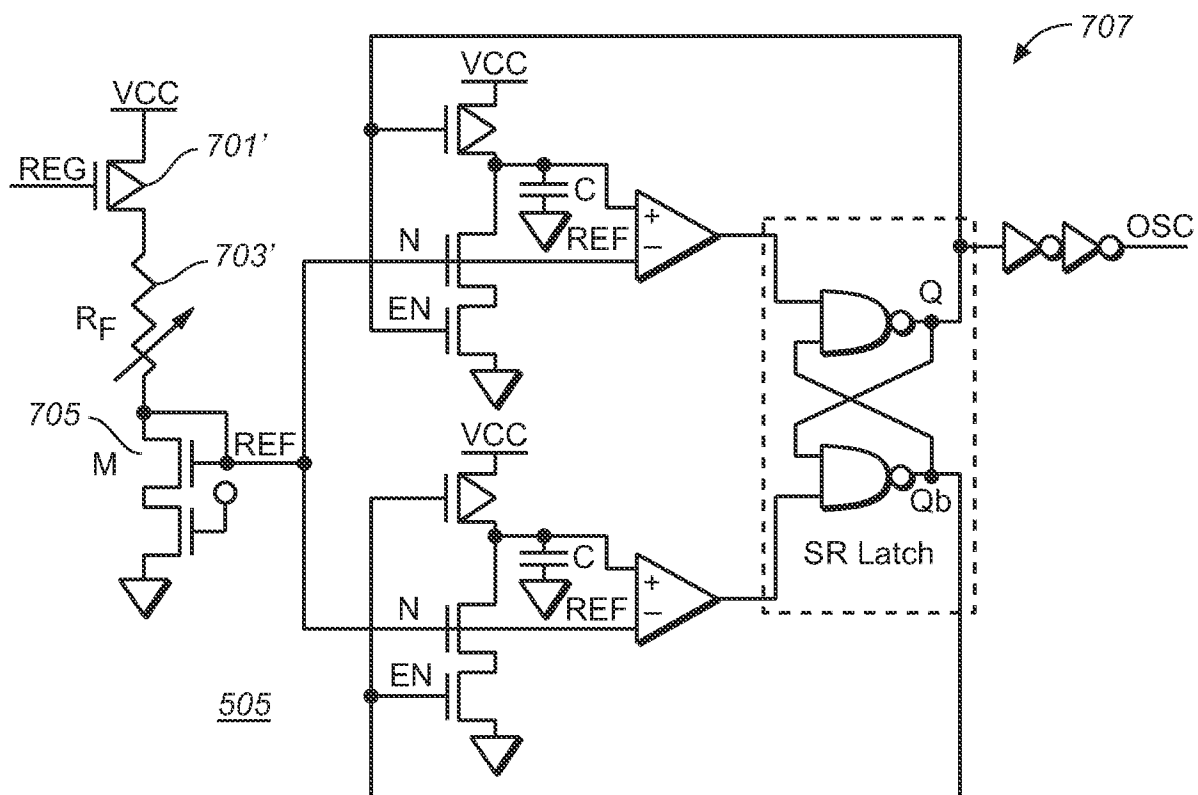
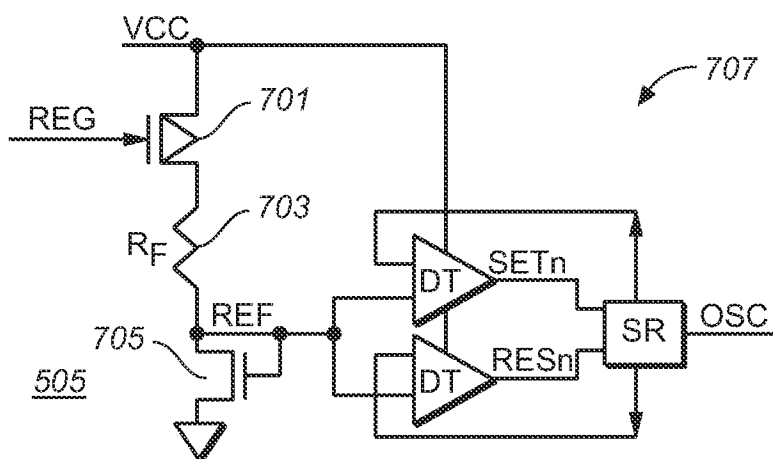
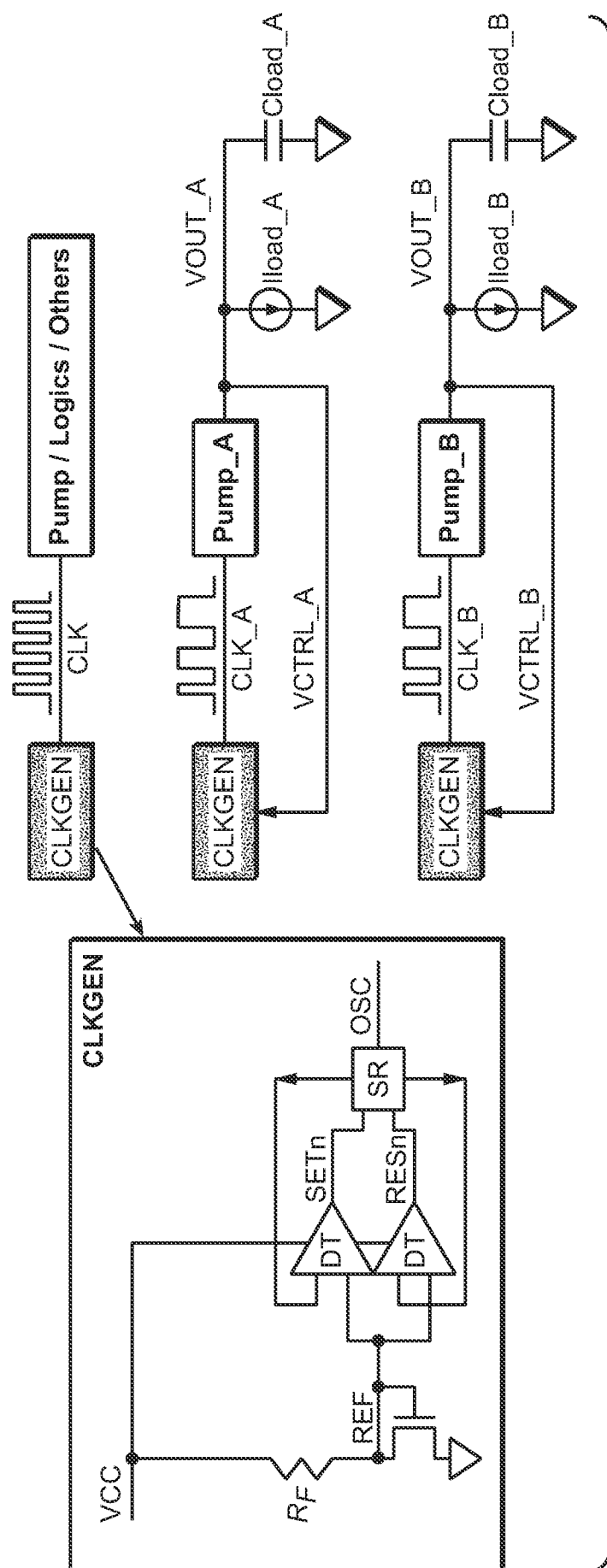


FIG. 6C

**FIG. 7**

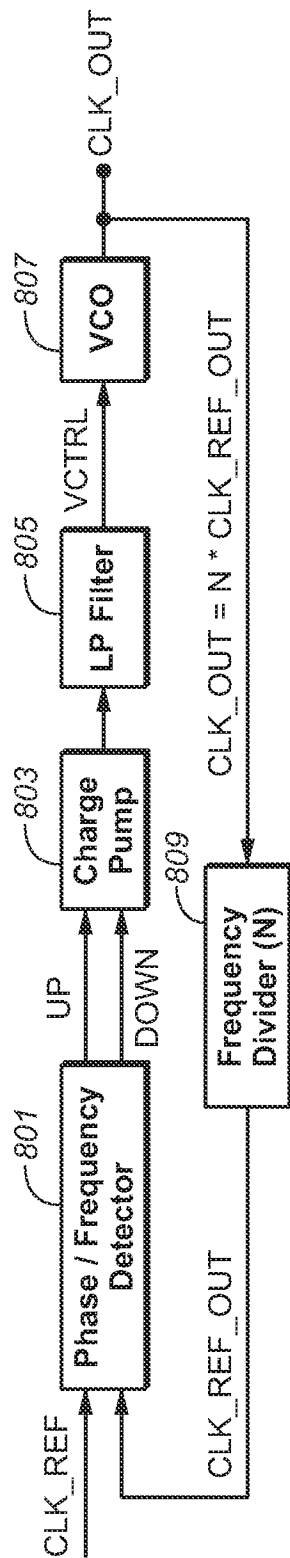


FIG. 8A

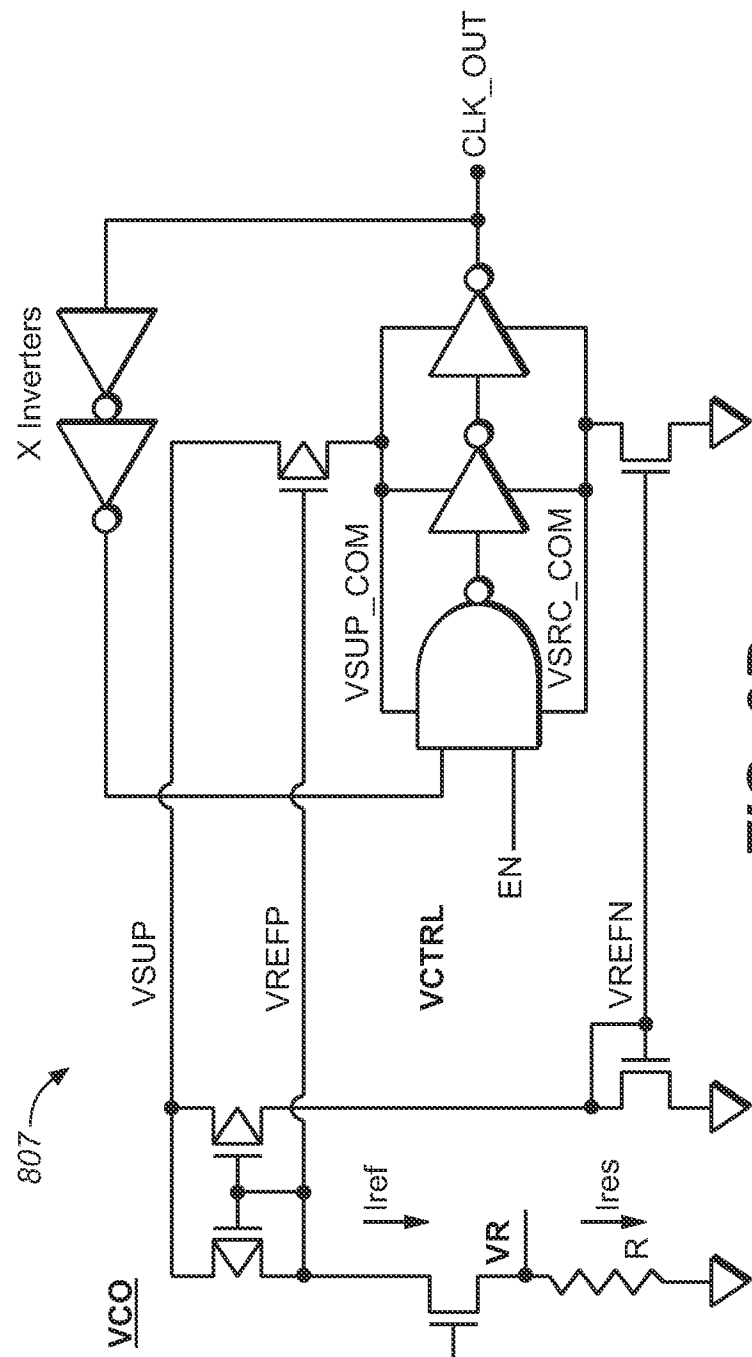
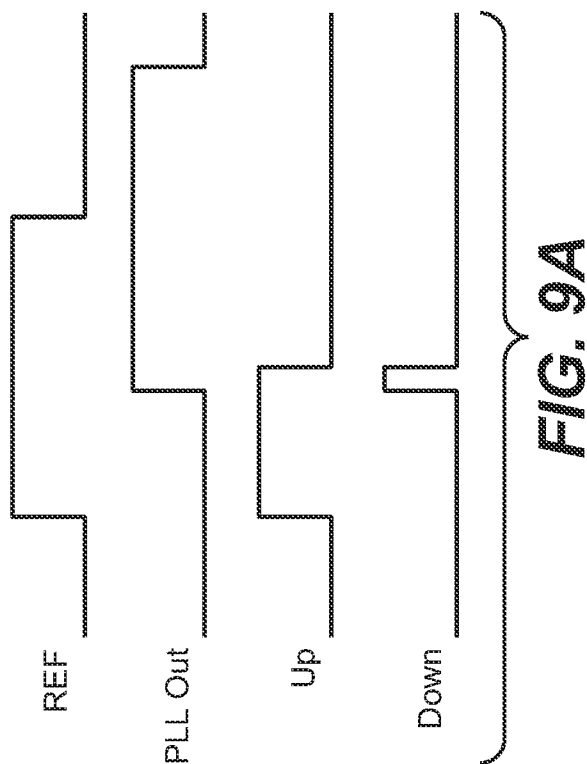
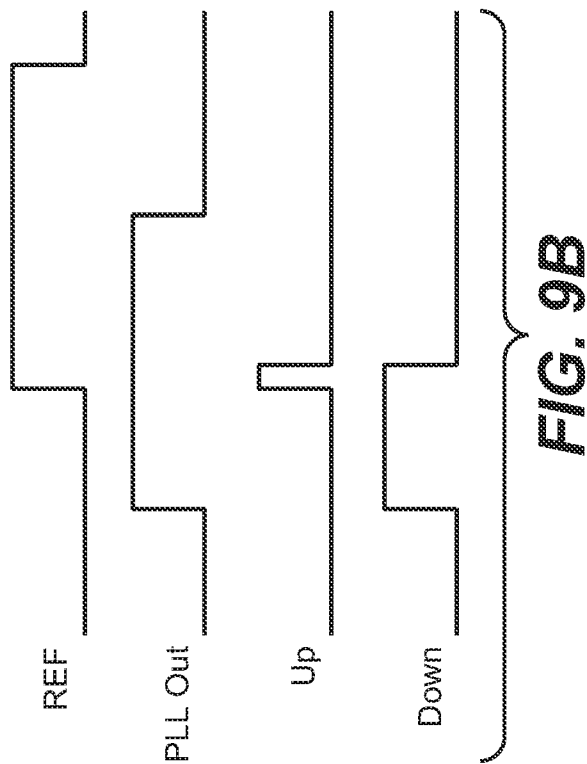


FIG. 8B



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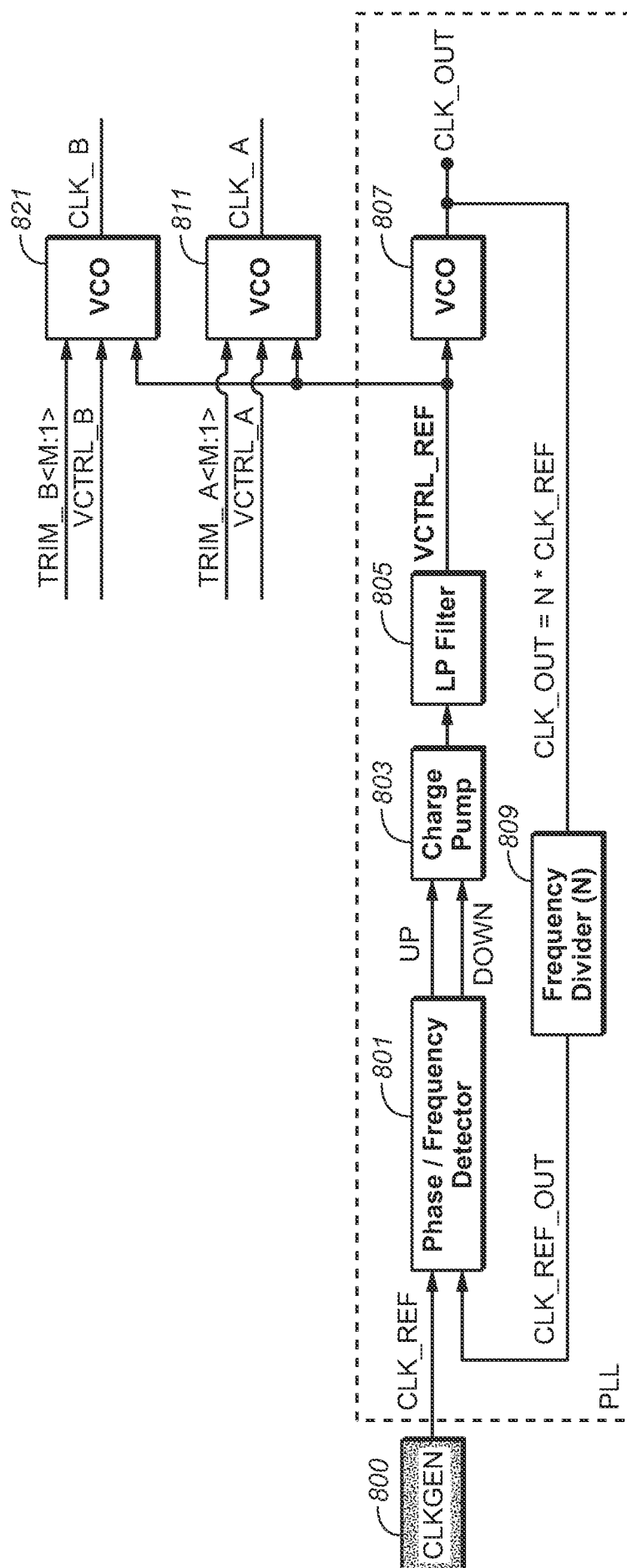


FIG. 10

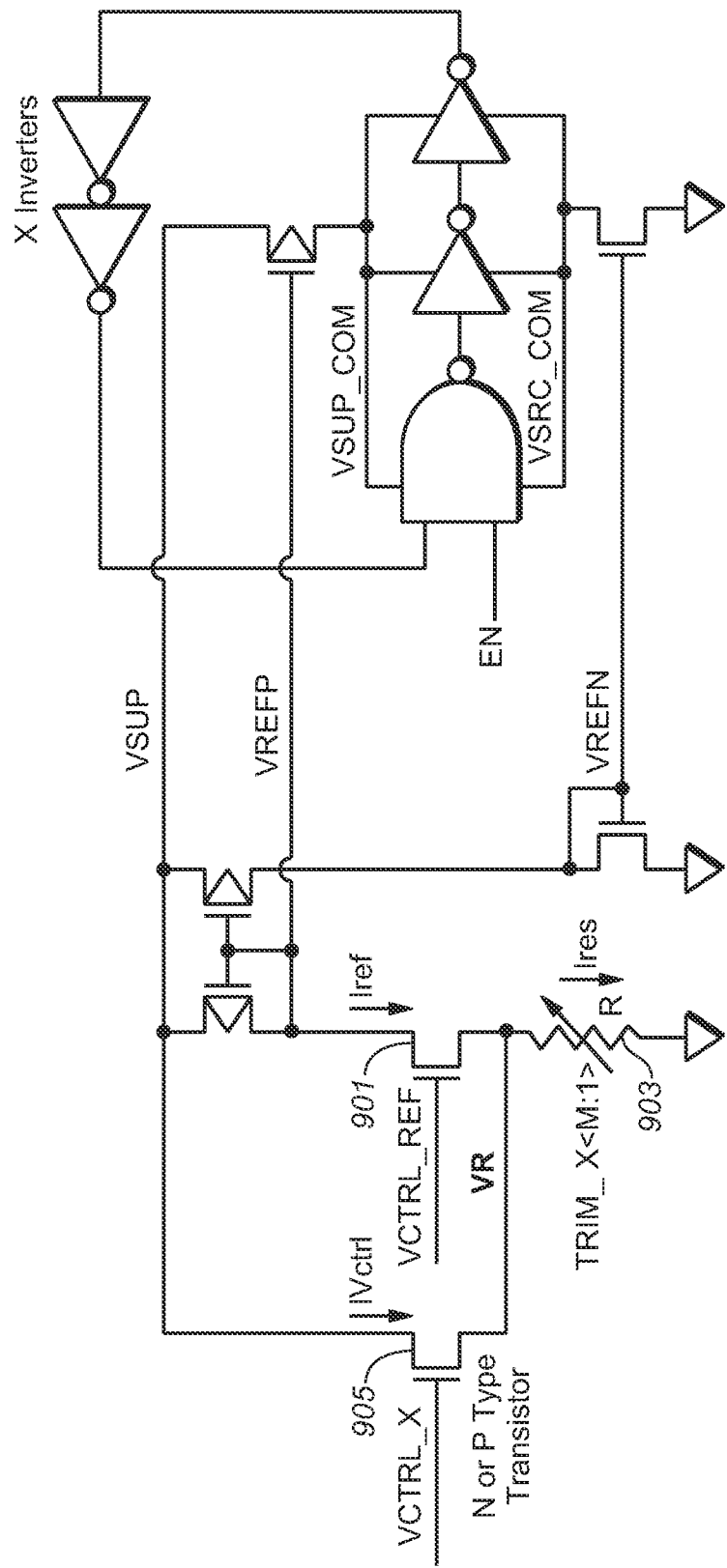
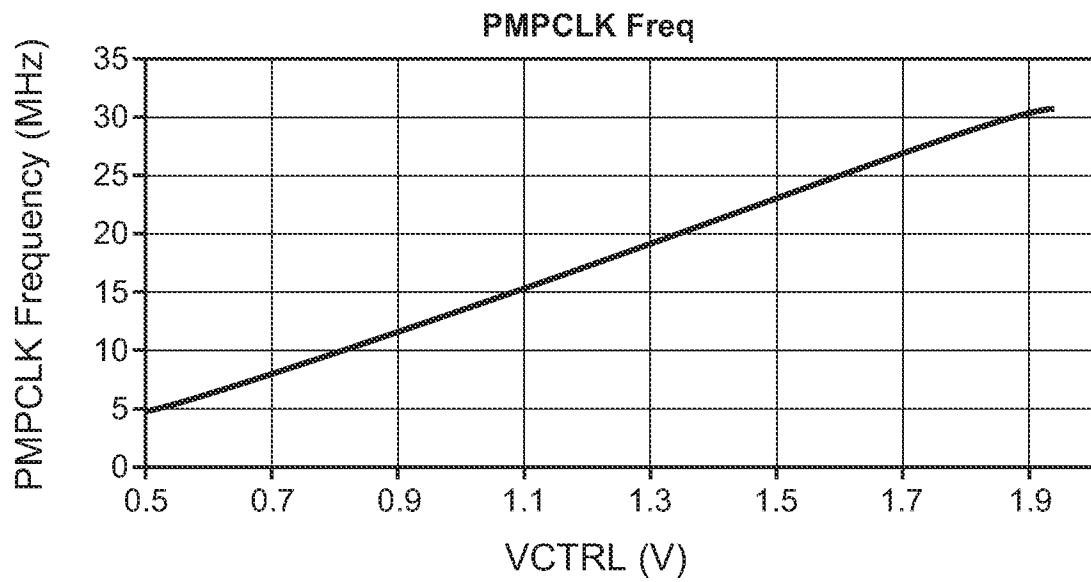
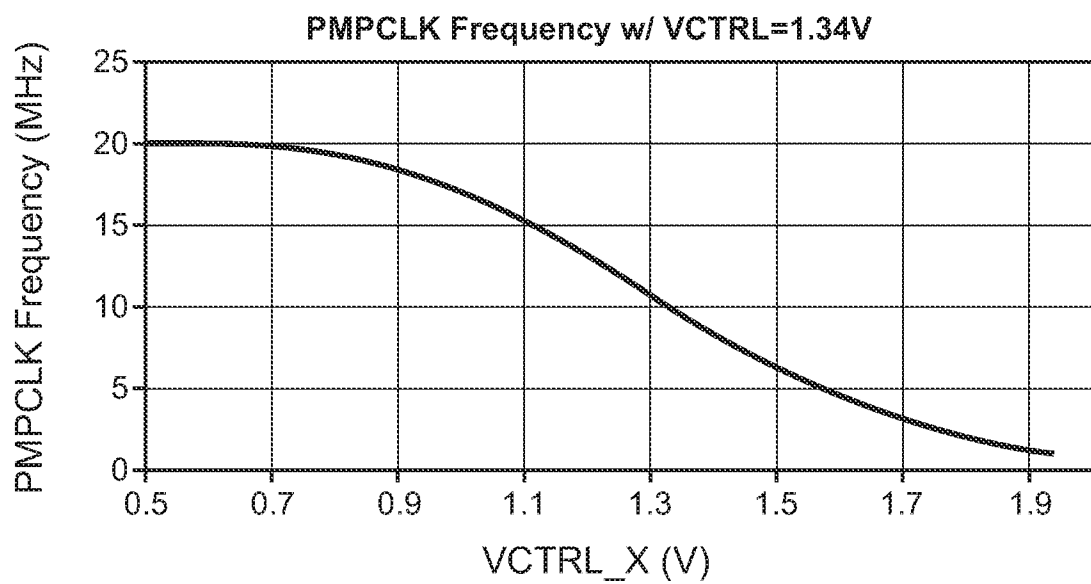


FIG. 11

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**FIG. 12A****FIG. 12B**

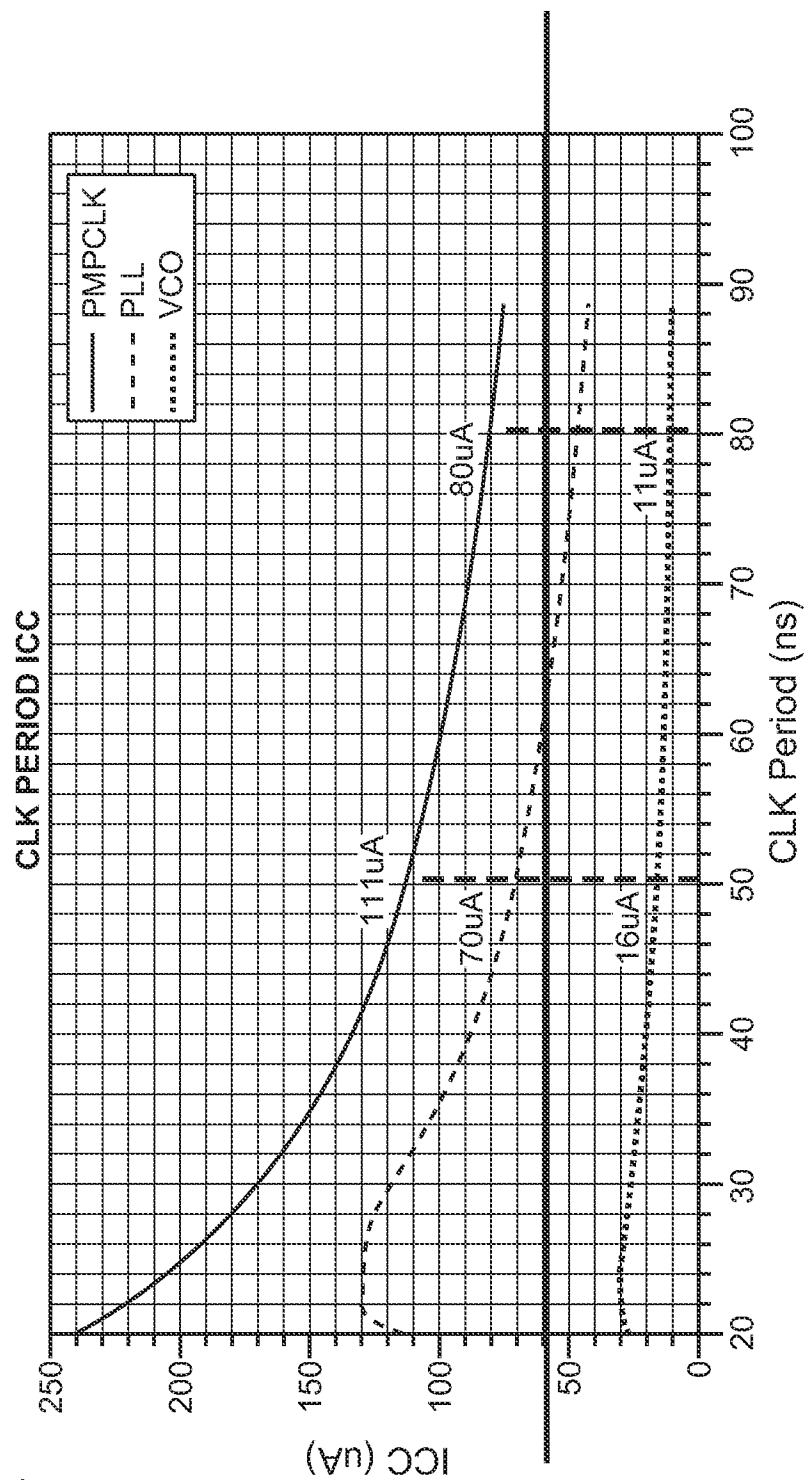


FIG. 13

	Period (ns)	Icc (uA)	Units	Icc (uA)
PMPCLK	@50	111	1	111
PMPCLK	@80	80	1	80
Total		191		
	Period (ns)	Icc (uA)	Units	Icc (uA)
PMPCLK	@200	60	1	60
PLL	@50	70	1	70
VCO	@80	11	1	11
Total		141		

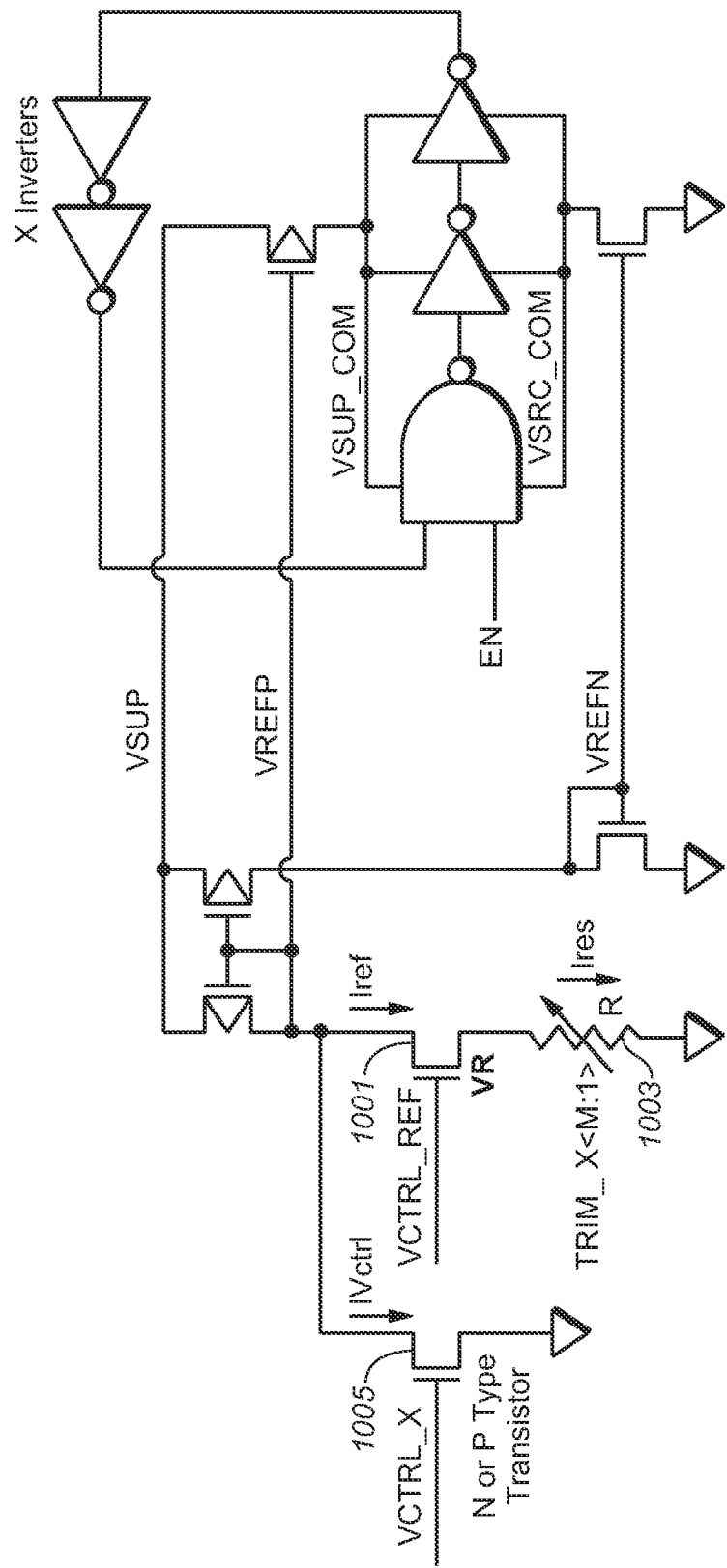


FIG. 14

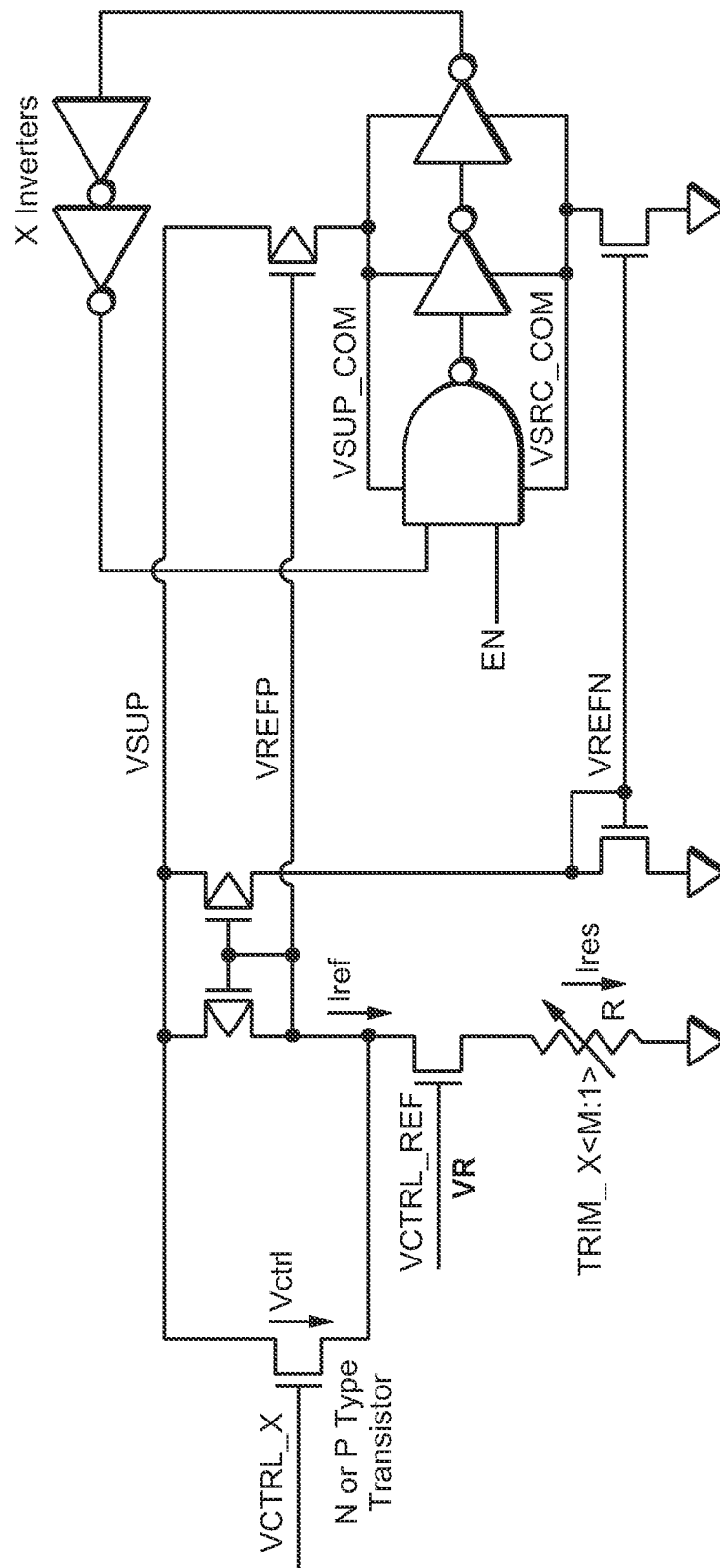


FIG. 15

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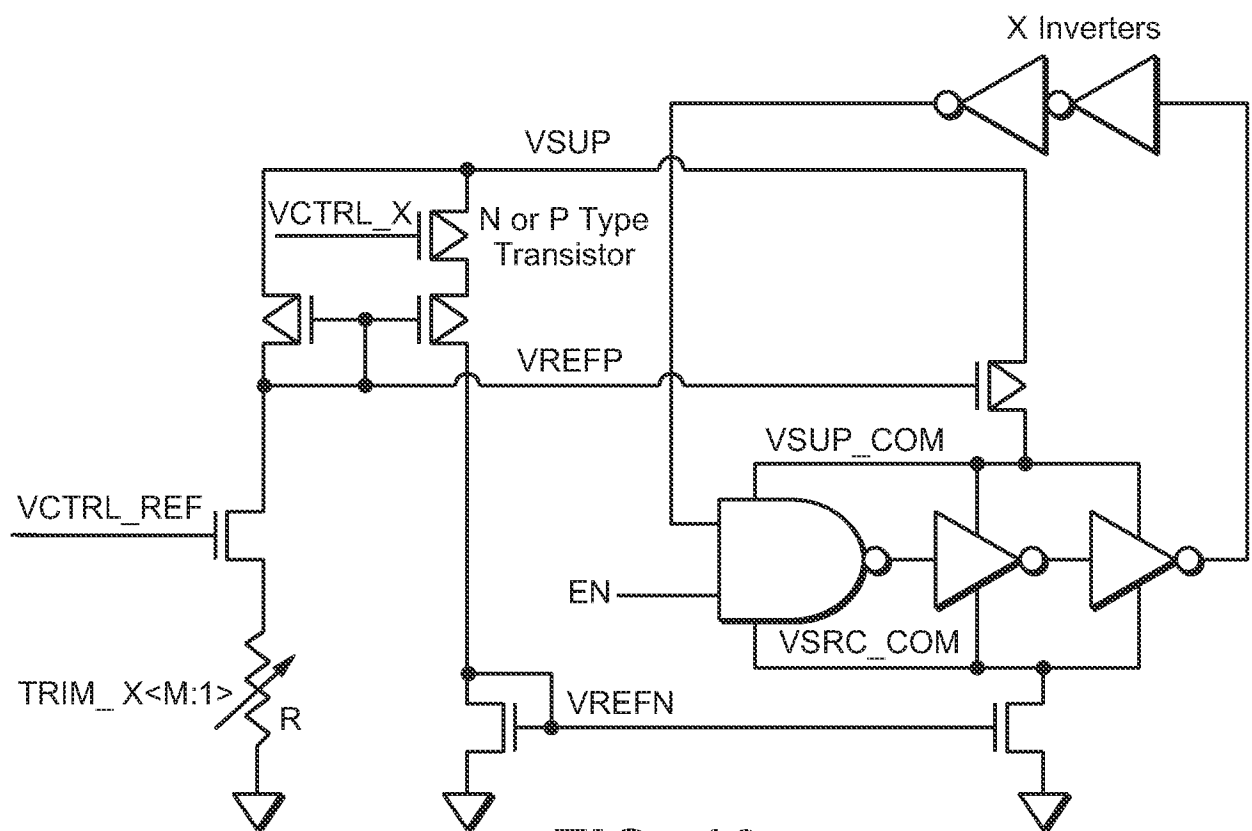


FIG. 16

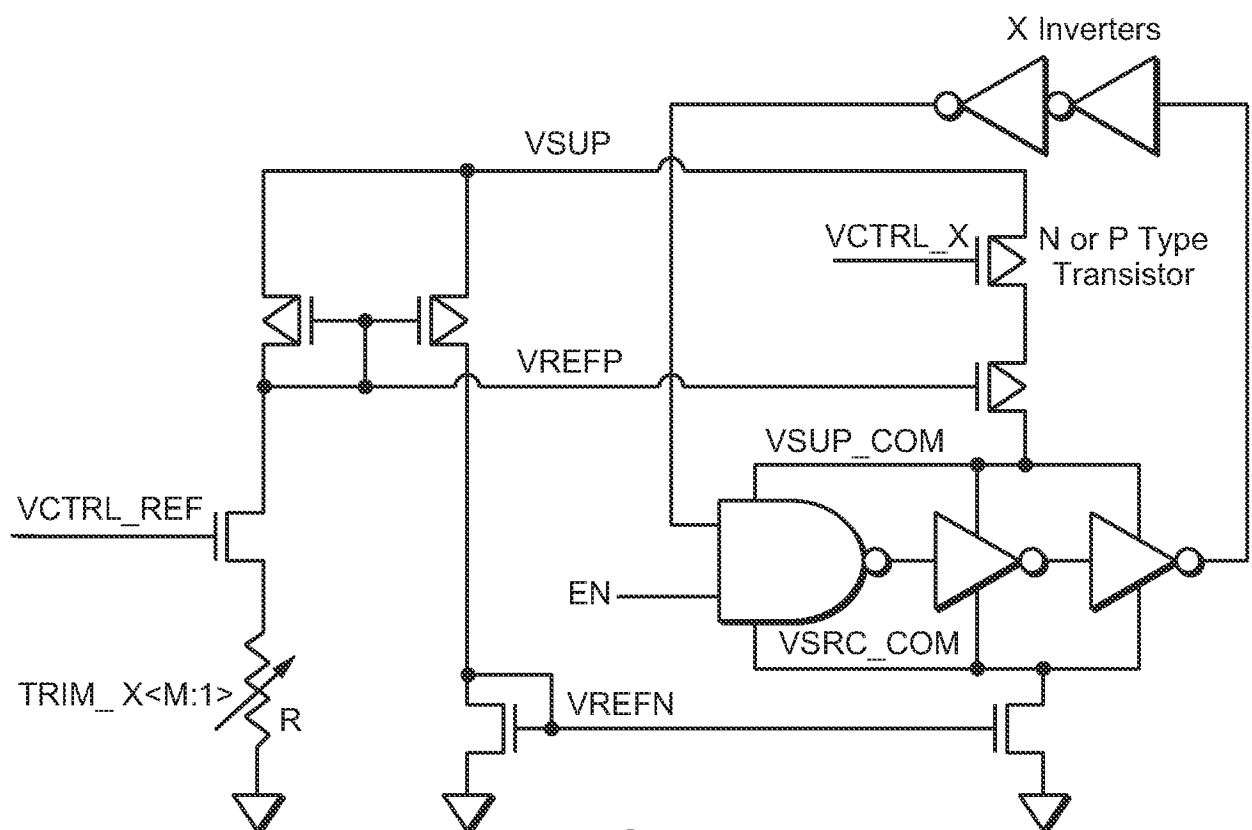
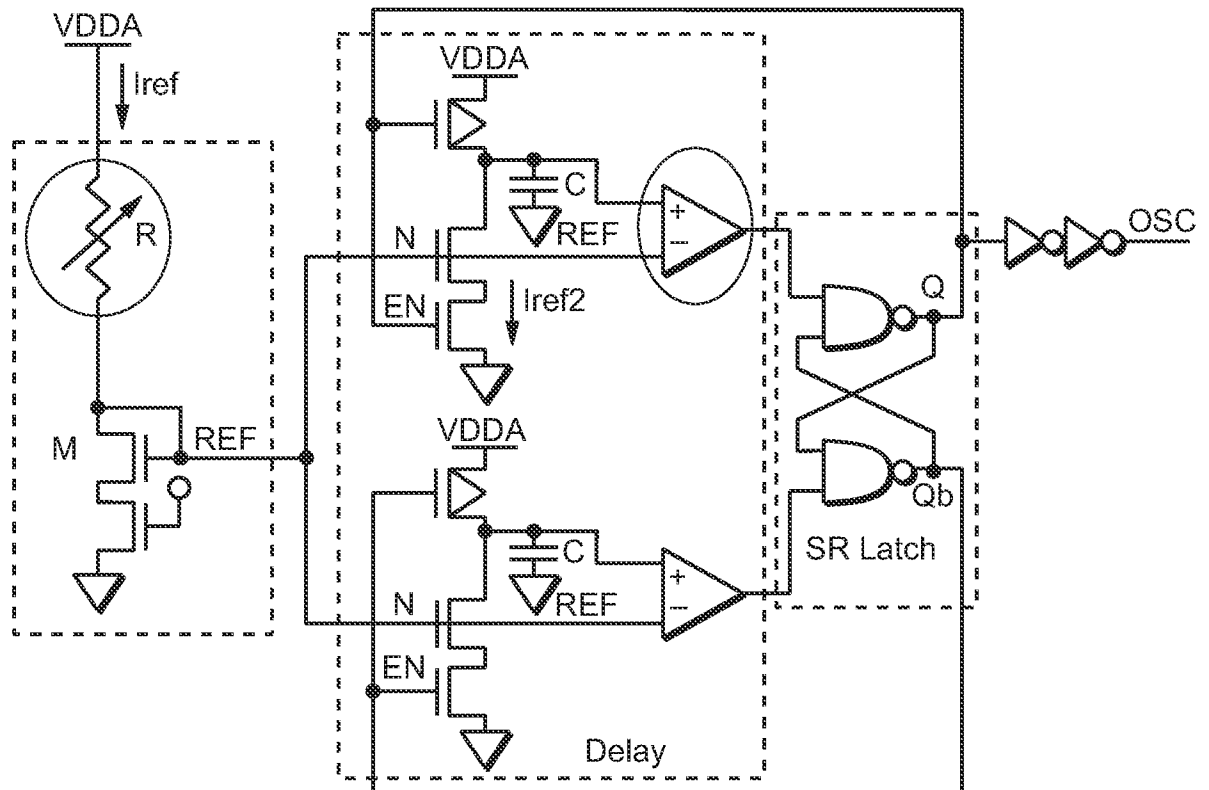
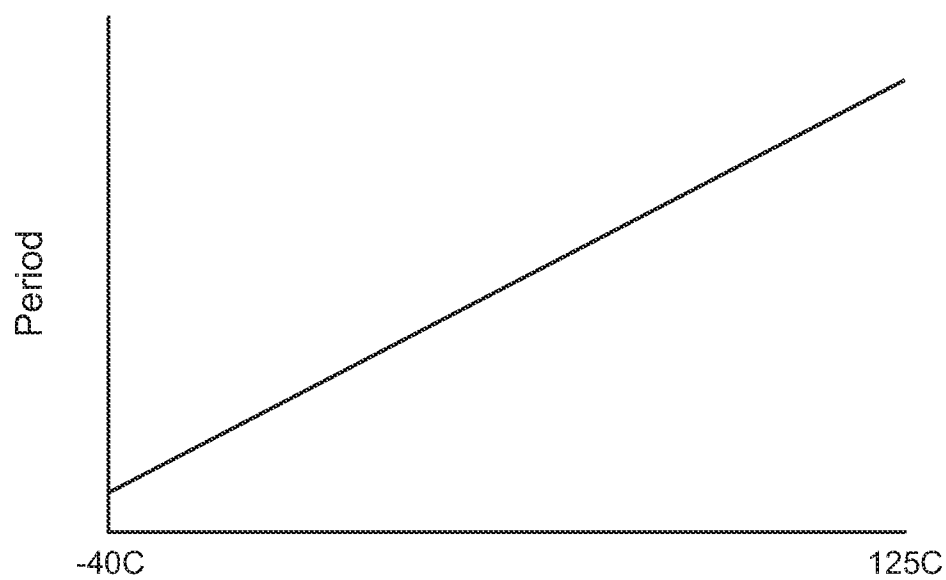


FIG. 17

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**FIG. 18****FIG. 19**

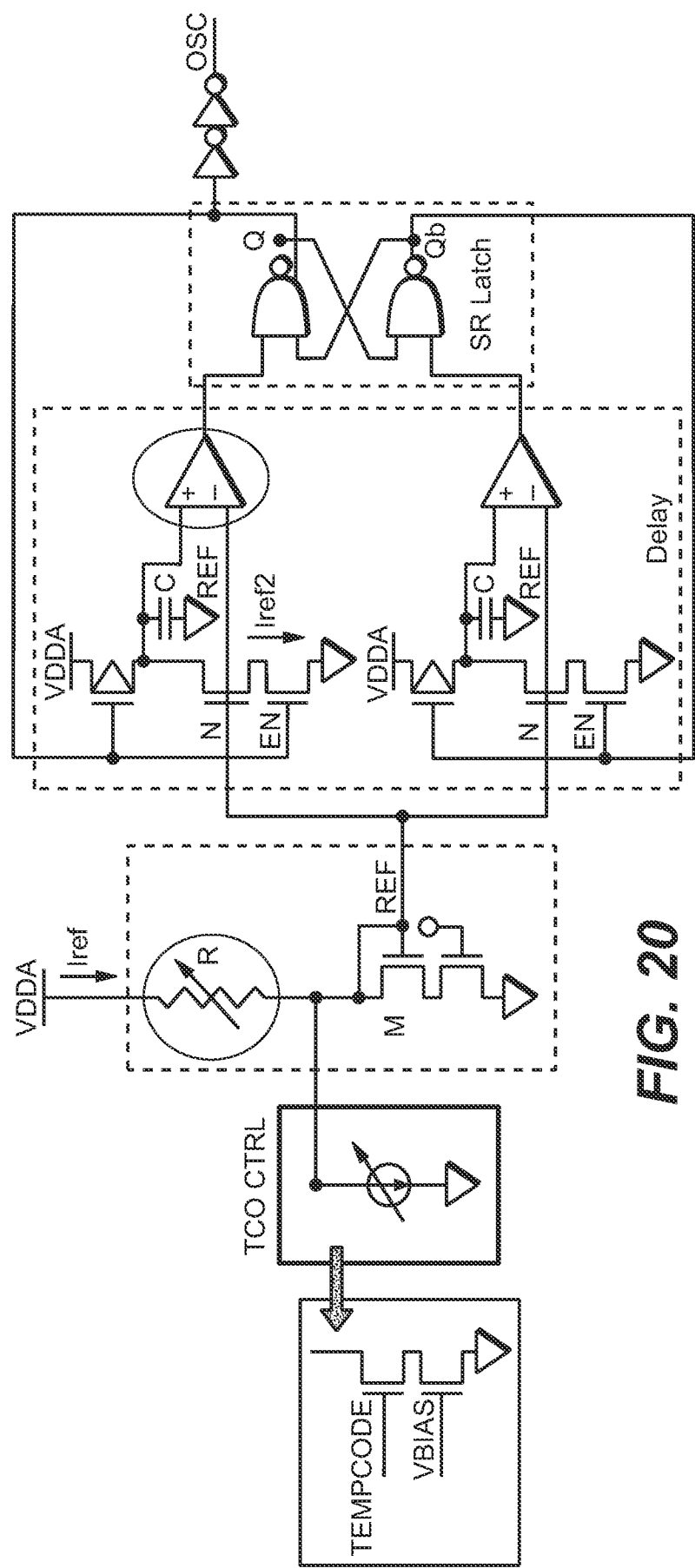


FIG. 20

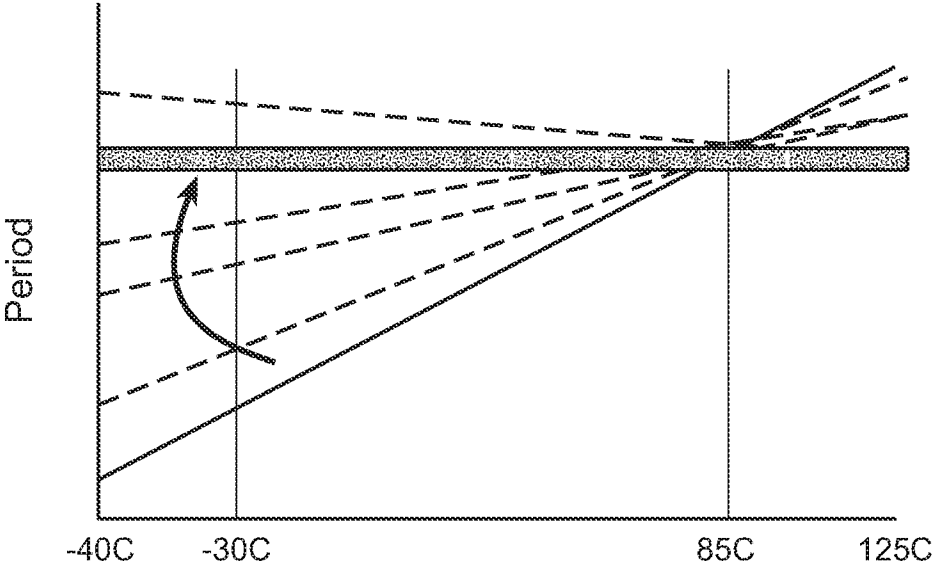


FIG. 21

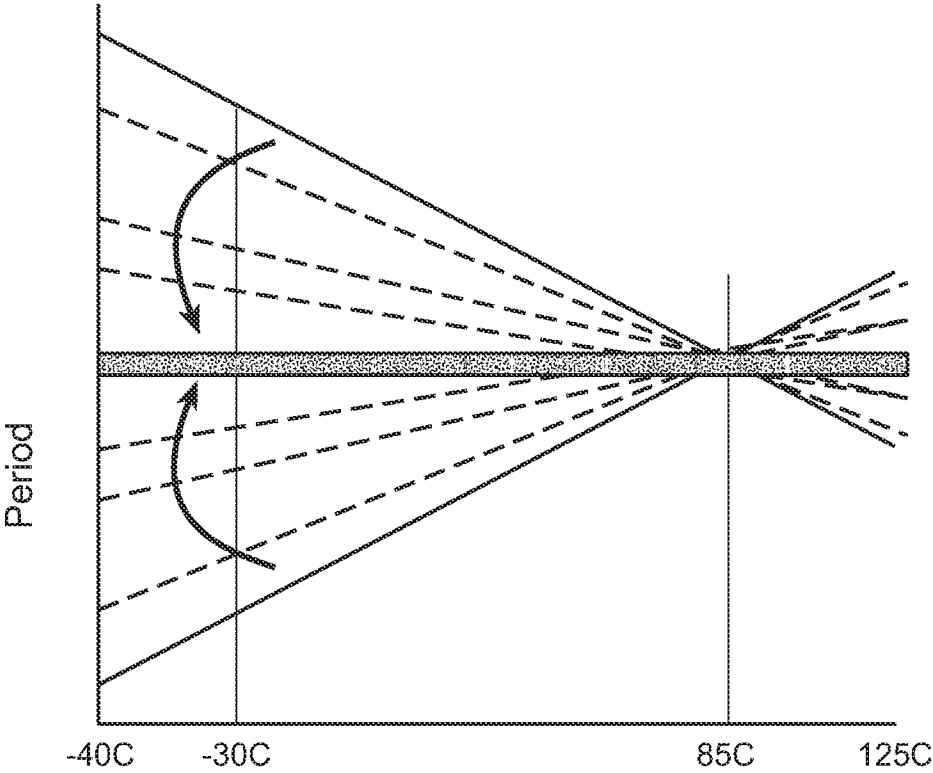


FIG. 23

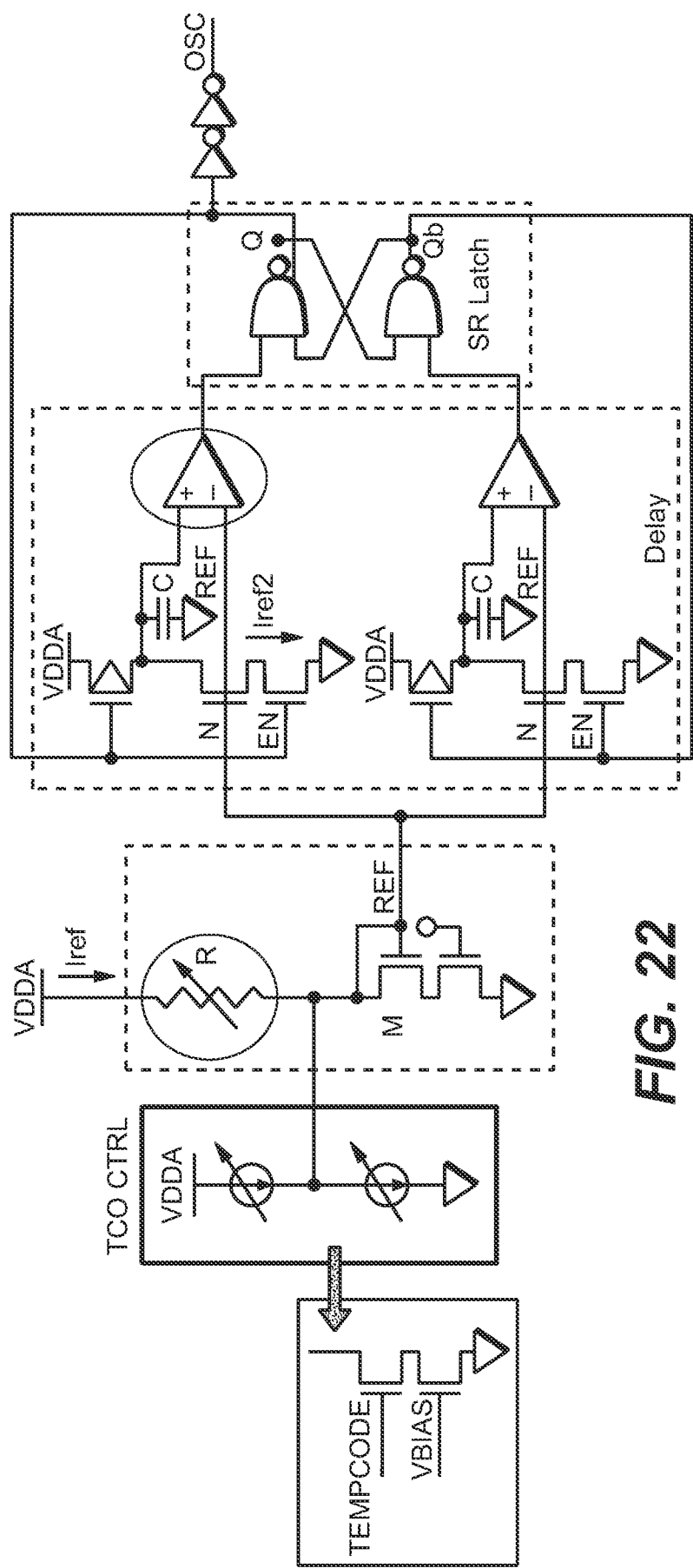


FIG. 22

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2015/017371

A. CLASSIFICATION OF SUBJECT MATTER

INV. H03K3/011 H03K3/0231
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)
H03K

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	CN 102 664 605 A (UNIV ELECTRONIC SCIENCE & TECH) 12 September 2012 (2012-09-12) the whole document	1,3-16, 18-21
X	WO 00/76069 A2 (MICROCHIP TECH INC [US]) 14 December 2000 (2000-12-14) figures 3-5	1,2,6,9, 10, 13-17, 19,21
X	GB 2 460 538 A (AVAGO TECH ECBU IP [SG] AVAGO TECH ECBU IP SG PTE LTD [SG]) 9 December 2009 (2009-12-09) abstract; figures 1-5	1,2,6, 9-11, 13-17, 19,21



Further documents are listed in the continuation of Box C.



See patent family annex.

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"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

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search

11 May 2015

Date of mailing of the international search report

22/05/2015

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Authorized officer

Mesplede, Delphine

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2015/017371

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