US 20010020875A1

(54) **METHOD AND APPARATUS FOR CALIBRATING A FREQUENCY ADJUSTABLE OSCILLATOR IN AN INTEGRATED CIRCUIT DEVICE**

(75) Inventor: **Lars Gustaf Jansson**, Bethel, ME (US)

Correspondence Address:
Martin J. Jaquez, Esq.
JAQUEZ & ASSOCIATES
750 B Street, Suite 2640
San Diego, CA 92101 (US)

(57)   **ABSTRACT**

A method and apparatus for digitally controlling the capacitance of an integrated circuit device using MOS-FET devices. In accordance with one aspect of the present invention, a one-bit or "binary" varactor is presented wherein the gate-to-bulk capacitance of the MOS-FET device exhibits dependency to a D.C. voltage applied between its gate and well implant regions. The capacitance-voltage characteristic of the binary capacitor has three major regions: (1) a first relatively flat region having little or no voltage dependency and having a capacitance equal to a first low capacitance of C_1; (2) a sloped region wherein a voltage dependency exists; and (3) a second relatively flat region where there is little or no voltage dependency and where the capacitance equals a second higher capacitance of C_2. The capacitance of the binary capacitor can be changed from C_1 to C_2 simply by changing the polarity of the applied D.C. voltage from a positive to a negative value. A plurality of binary capacitors are configured in a parallel arrangement to produce a digitally controlled capacitor. The digitally controlled capacitor can be used in any integrated circuit requiring a tightly controlled tuned network. One application is a voltage-controlled oscillator (VCO) wherein the center output frequency of the VCO is calibrated by digitally modifying the capacitance of the VCO's digitally controlled capacitor. A means for determining whether the VCO requires calibration and a means for calibrating the center output frequency of the VCO is presented.

100
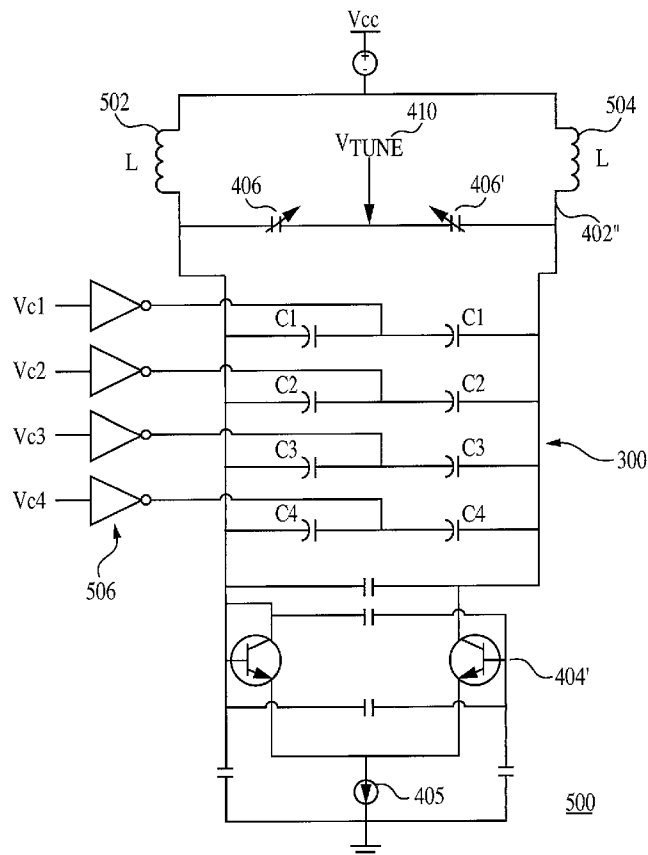
FIGURE 1
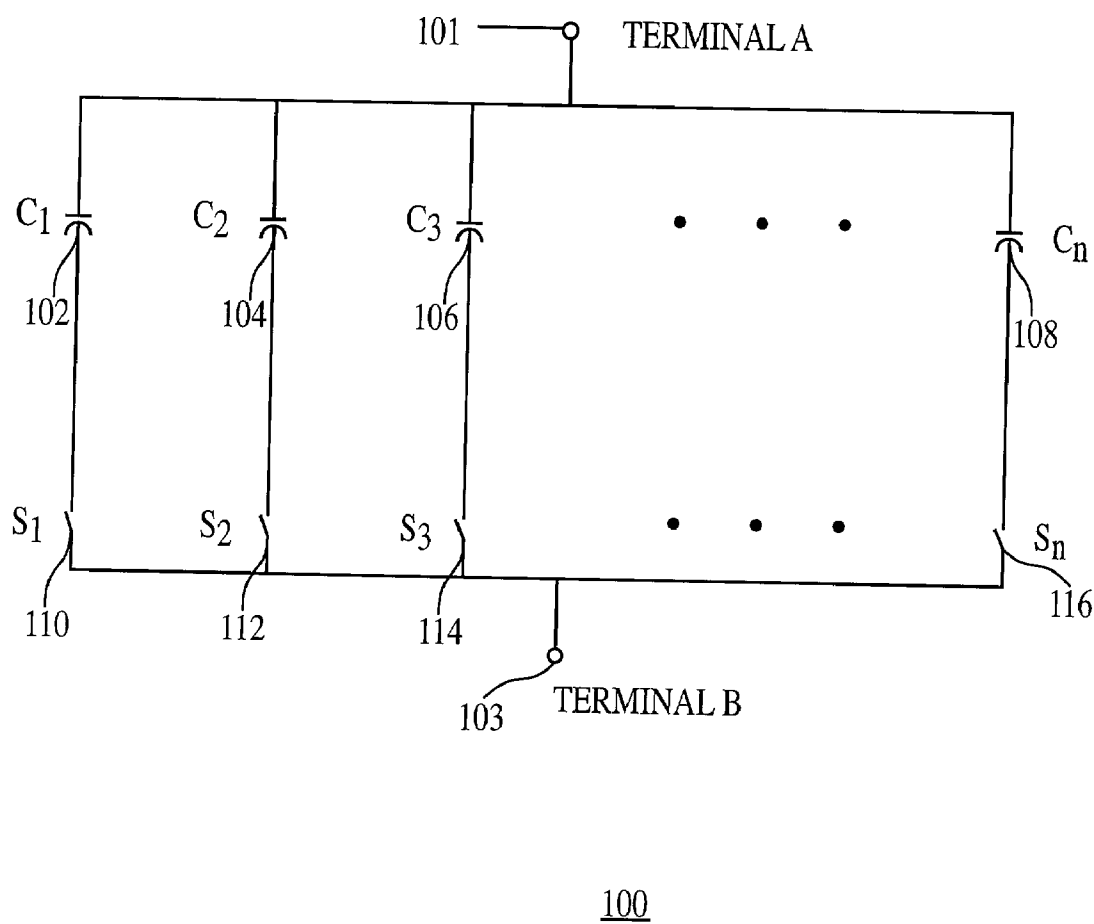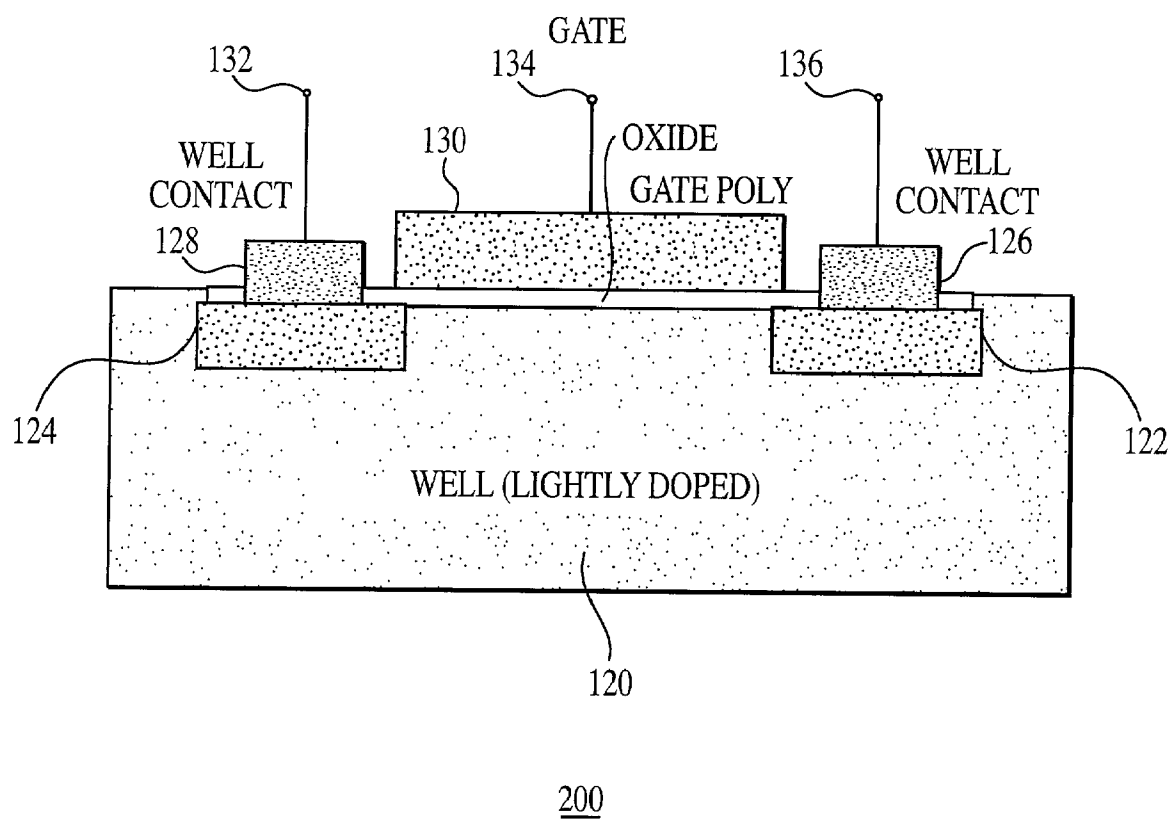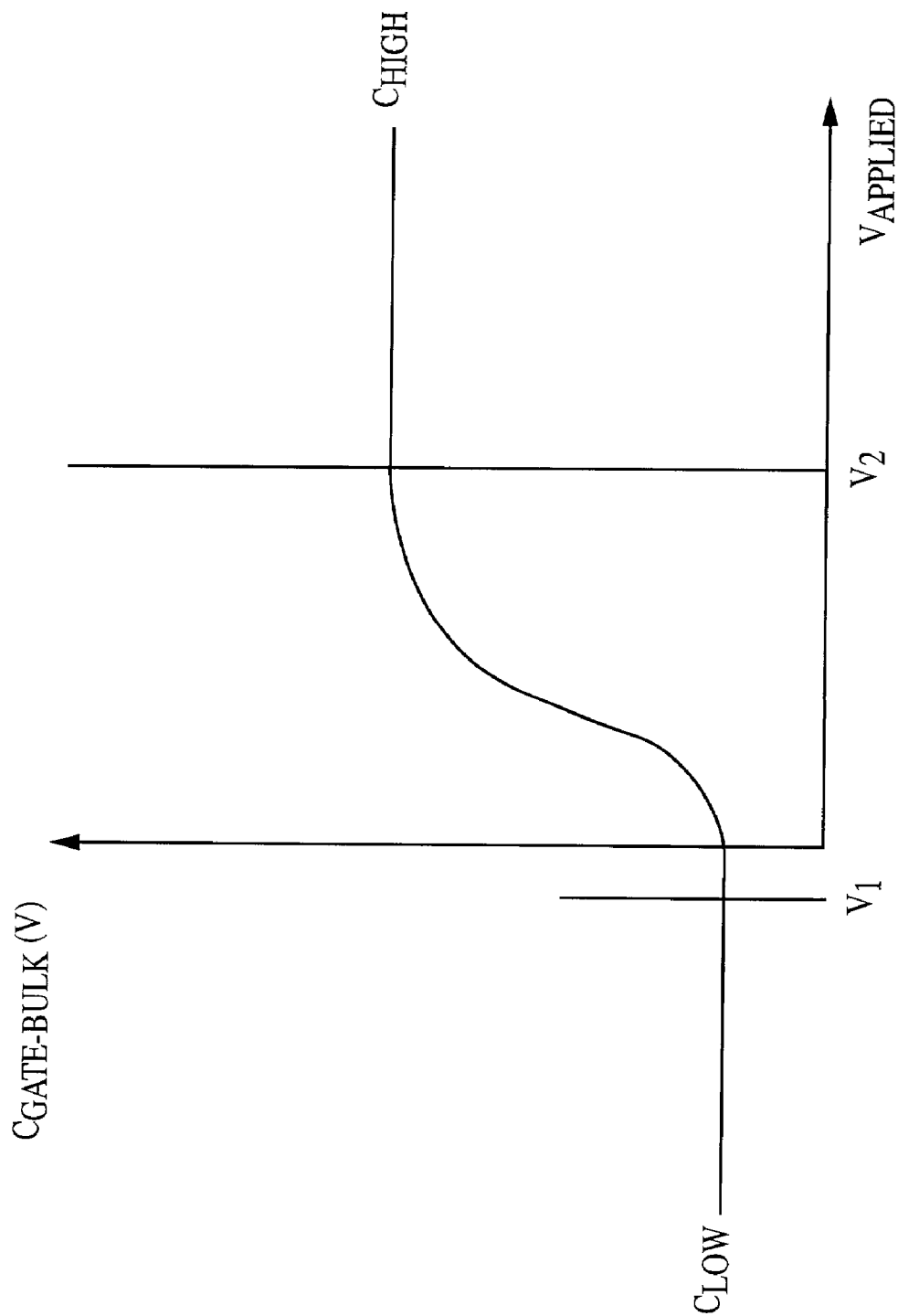## (PRIOR ART)

FIGURE 2

FIGURE 3
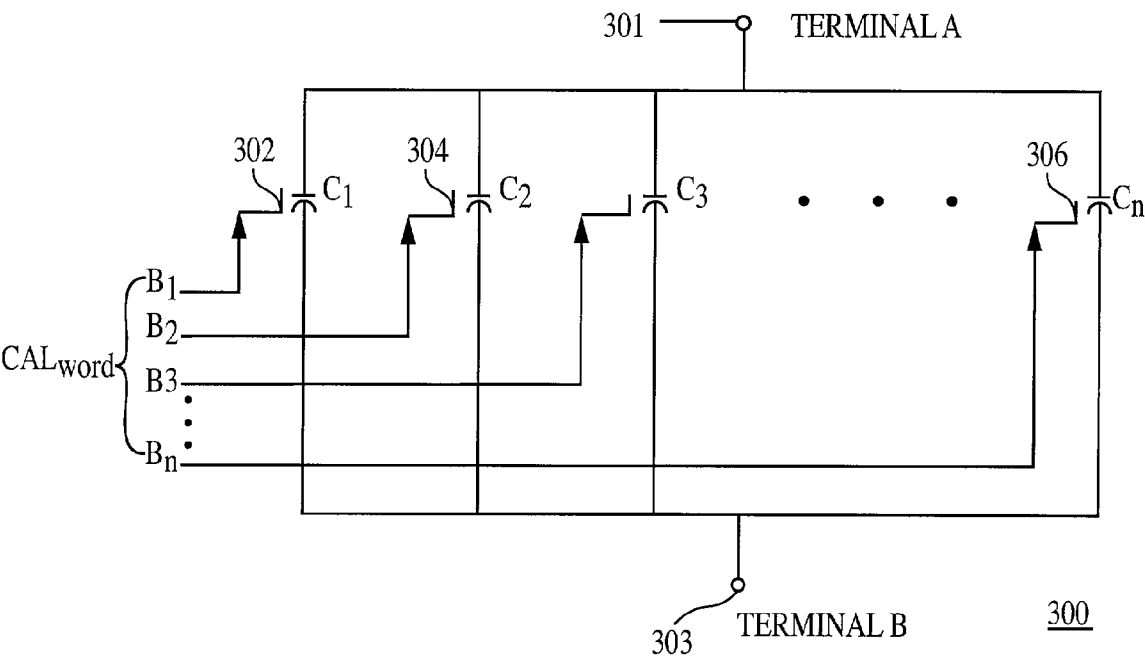
FIGURE 4a
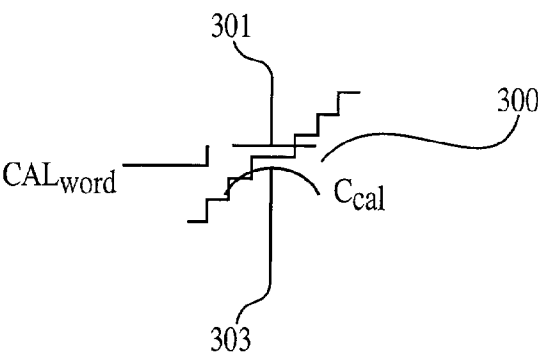
FIGURE 4b
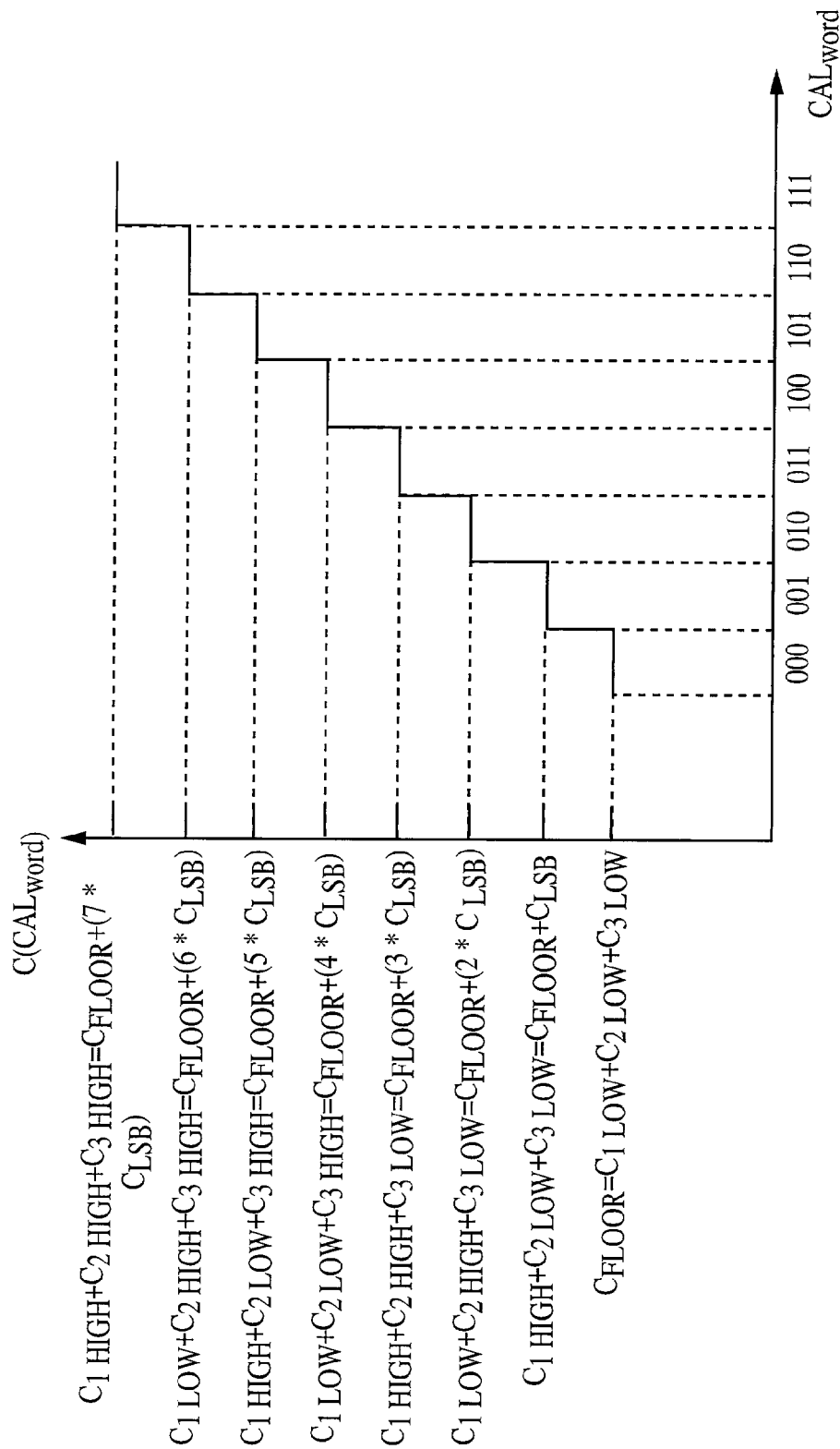
FIGURE 5
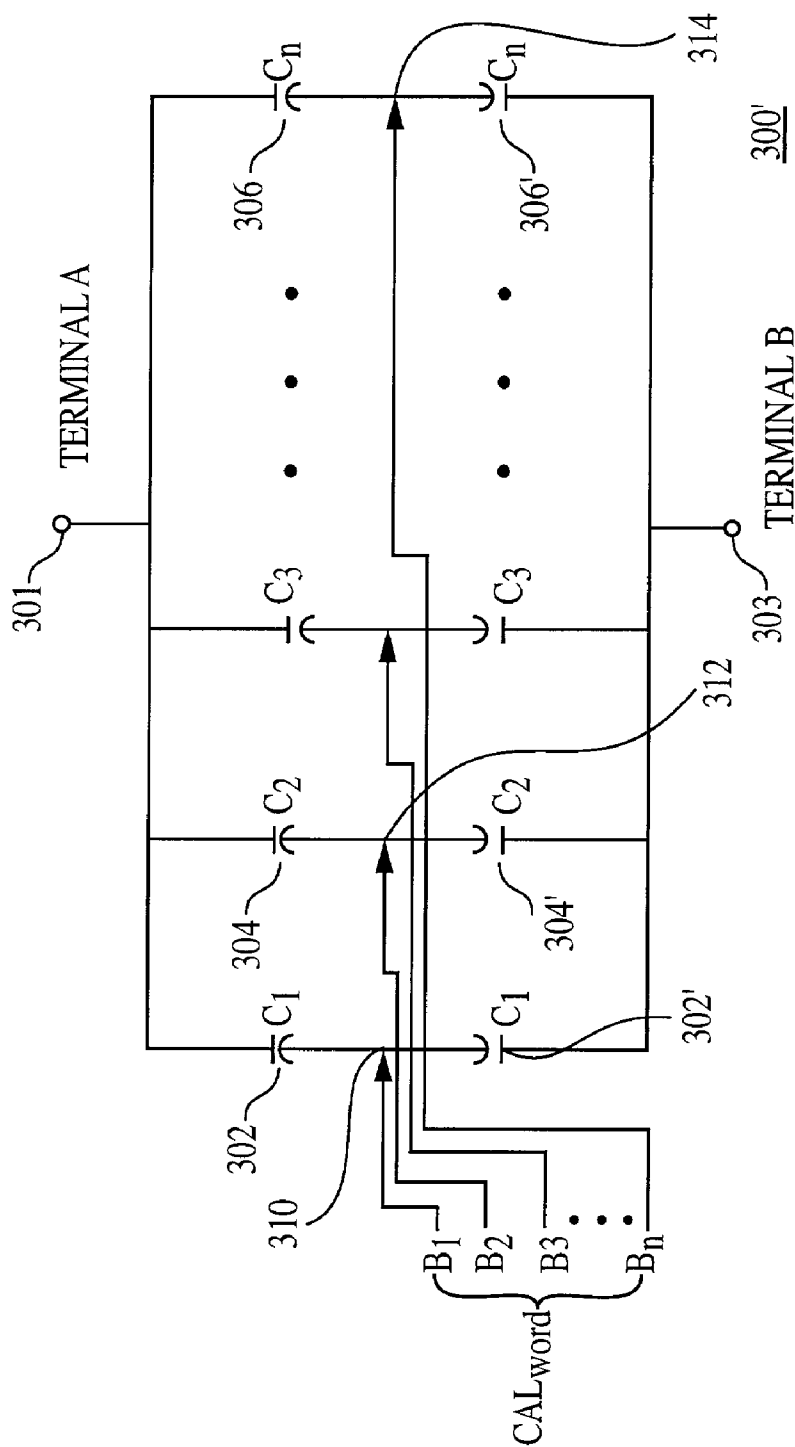
FIGURE 6
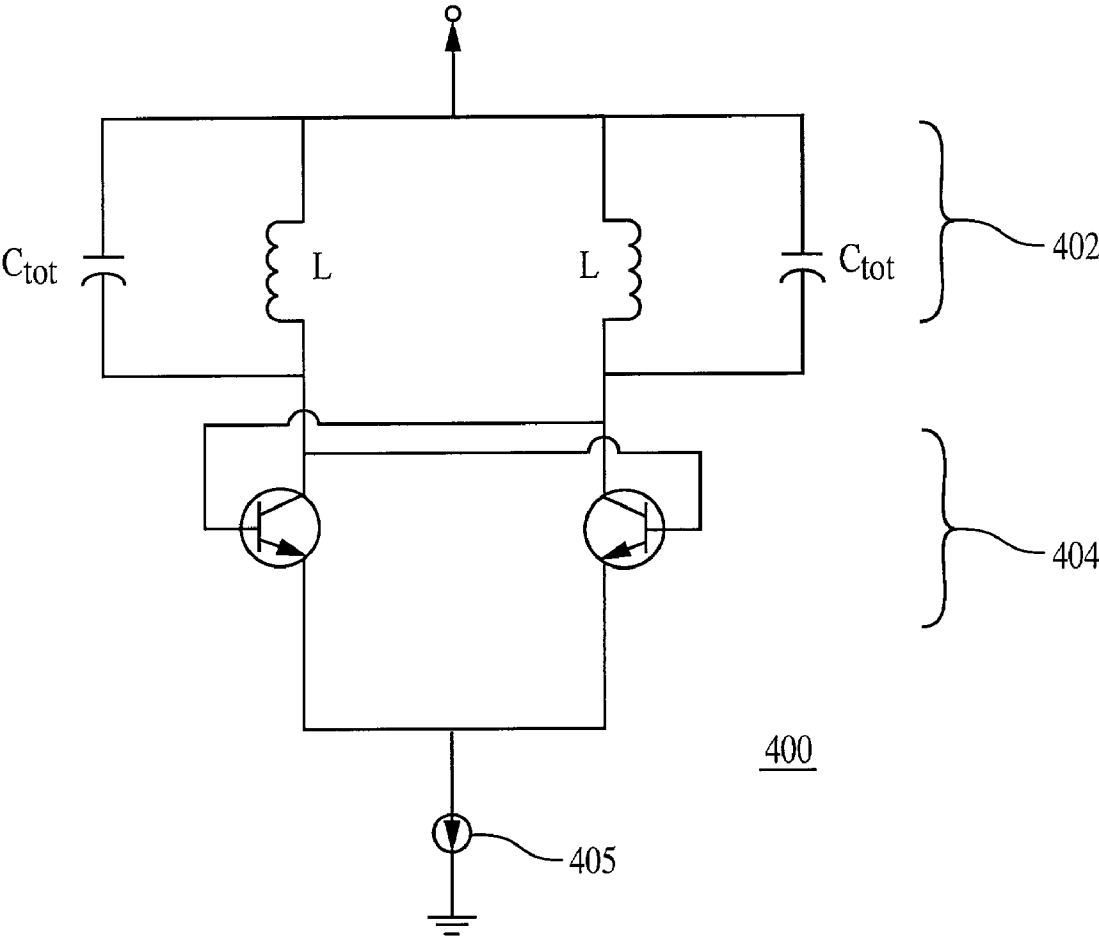
FIGURE 7

FIGURE 8

FIGURE 9

410

V$_{TUNE}$

L   L

CAL$_{WORD}$

300

500

405
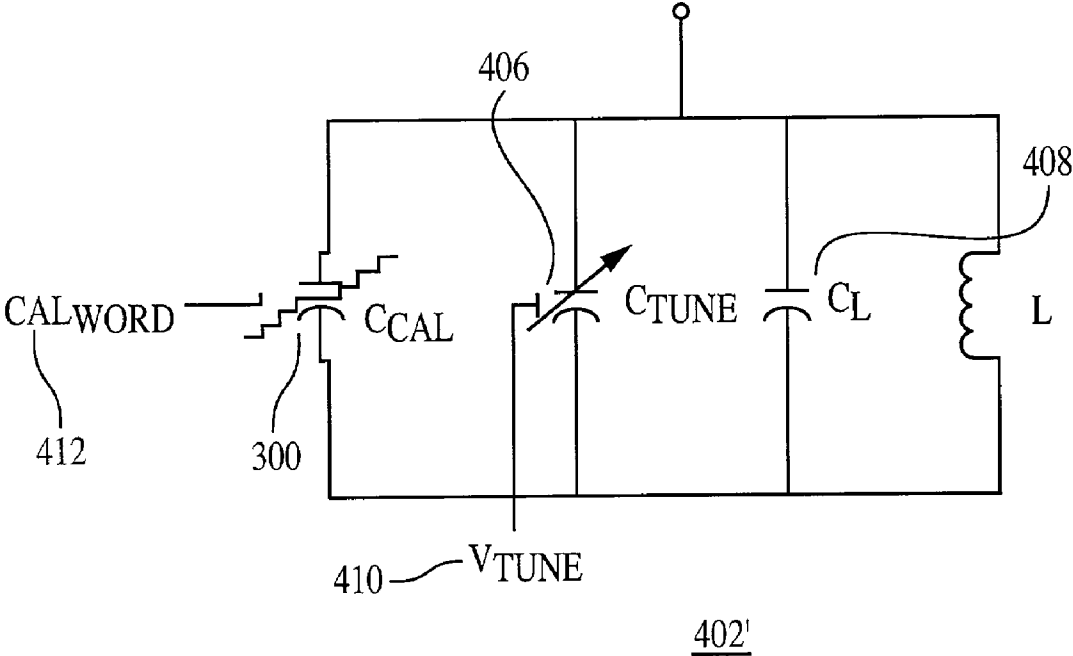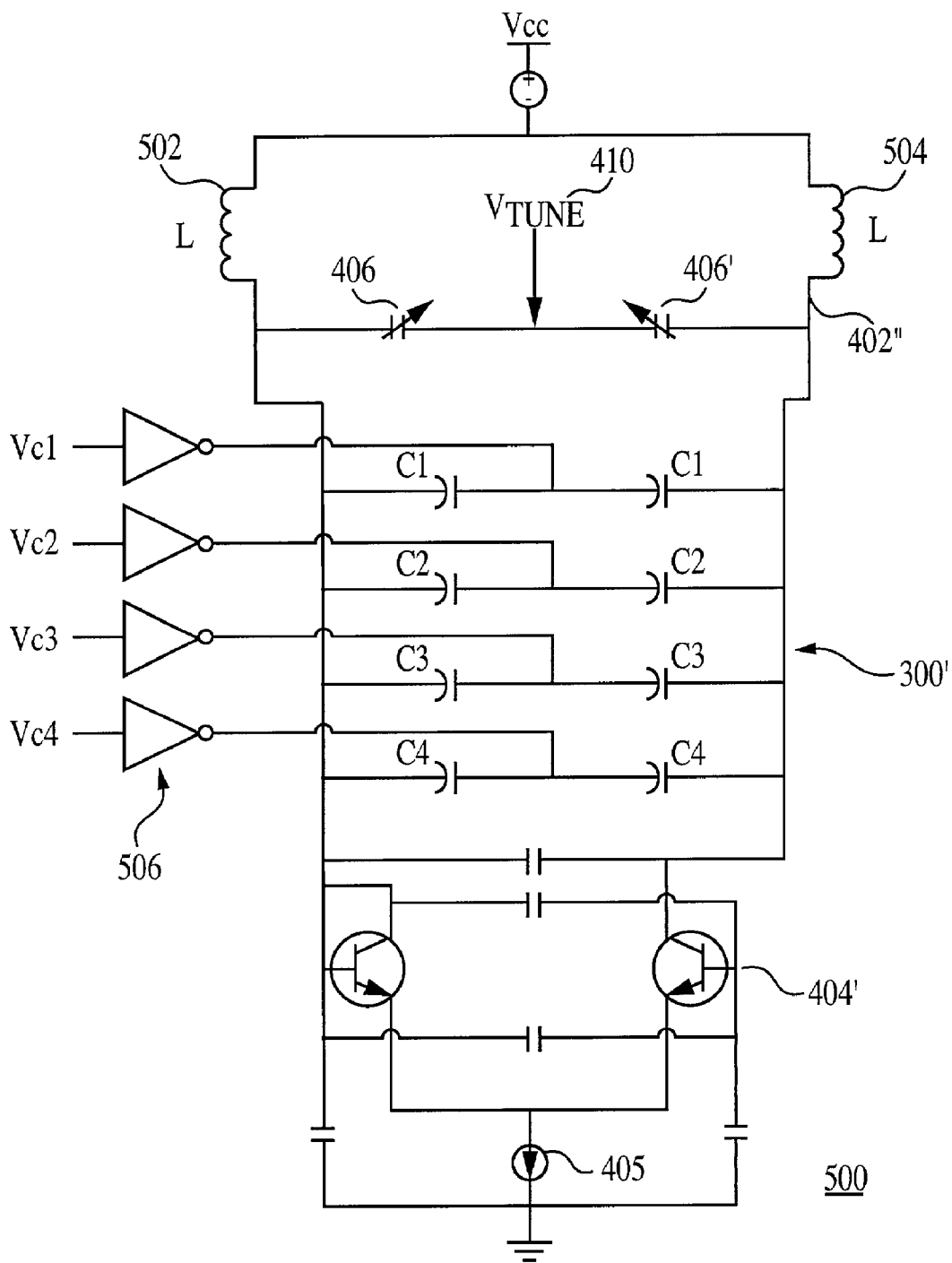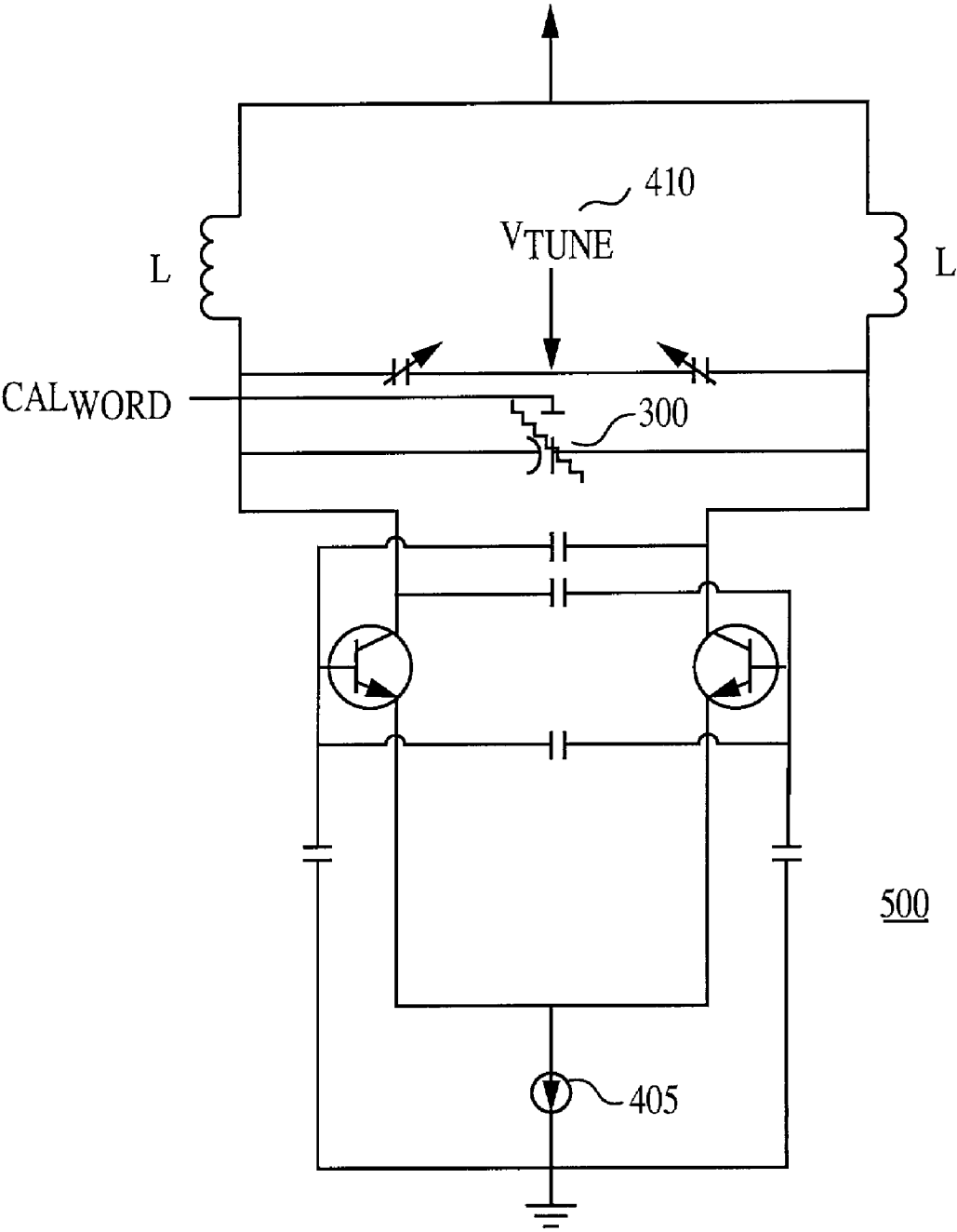
FIGURE 10

FIGURE 11

FIGURE 12

STEP 801 — INITIATE VCO CALIBRATION METHOD UPON POWERUP

INITIALIZE CALWORD TO "1000" — STEP 802

STEP 804 — WAIT $X_1 * T_{SETTLE}$

STEP 806 — RX OR TX? — YES

NO

STEP 808 — CHANNEL JUMP $> +/- N_{LSB}$? — YES

STEP 810 — CALWORD <-- CALWORD +/- N BITS

NO

$V_{TUNE} < V_{OUT}L$? — STEP 812

YES

NO

WAIT $X_2 * T_{SETTLE}$ — STEP 814

$V_{TUNE} > V_{OUT}H$? — STEP 816 — YES

$V_{TUNE} < V_{OUT}L$? — STEP 818 — NO

YES

INCREASE CALWORD by 1 bit (CALWORD <- CALWORD+1) — STEP 820

STEP 822 — $V_{TUNE} > V_{OUT}H$? — NO

WAIT $X_2 * T_{SETTLE}$ — STEP 824

STEP 826 — $V_{TUNE} < V_{OUT}L$? — YES

NO

STEP 828 — $V_{TUNE} > V_{OUT}H$? — NO

YES

DECREASE CALWORD by 1 bit (CALWORD <- CALWORD-1) — STEP 830

800

FIGURE 13

METHOD AND APPARATUS FOR CALIBRATING A FREQUENCY ADJUSTABLE OSCILLATOR IN AN INTEGRATED CIRCUIT DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This is application is a divisional application of U.S. application Ser. No. 09/304,443, filed May 3, 1999, entitled "Method and Apparatus for Digitally Controlling the Capacitance of an Integrated Circuit Device Using MOS-Field Effect Transistors", to issue on Apr. 3rd, 2001 as U.S. Pat. No.: 6,211,745.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] This invention relates to integrated circuit devices, and more particularly to a method and apparatus for digitally controlling the capacitance of integrated circuit components using MOS field effect transistors.

[0004] 2. Description of Related Art

[0005] One well-known problem to those skilled in the art of the design and manufacture of integrated circuits is the poor tolerance values associated with integrated circuit components, especially the tolerance values of passive circuit components. Due to process variations, device parameter spread, variations in critical parameters such as conductive layer sheet resistance values, f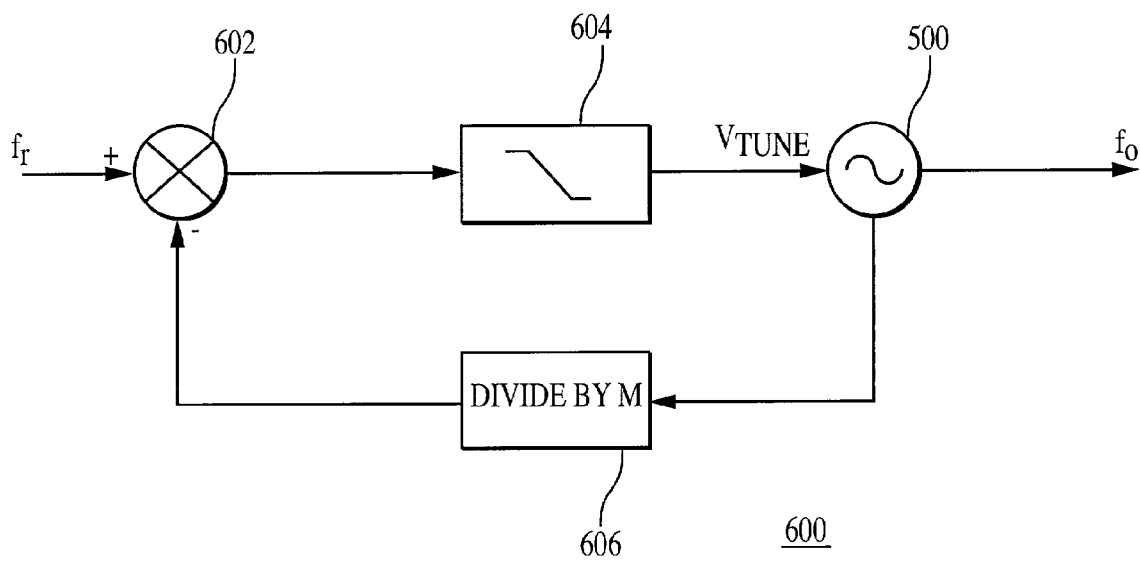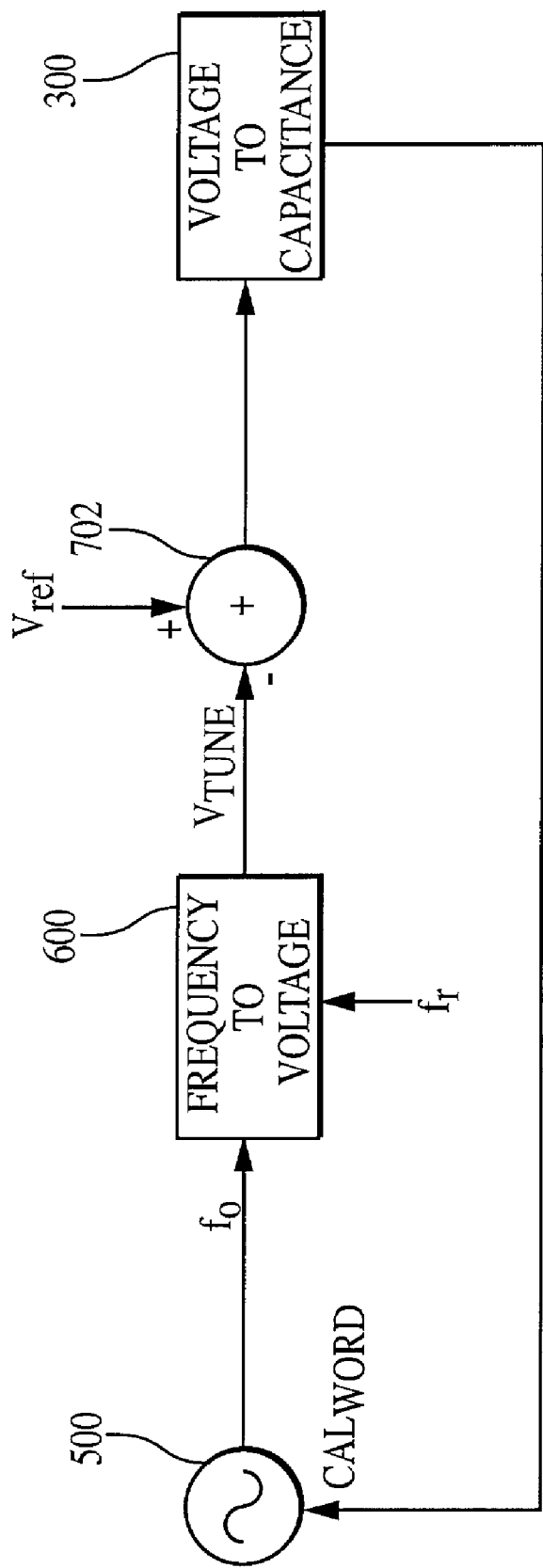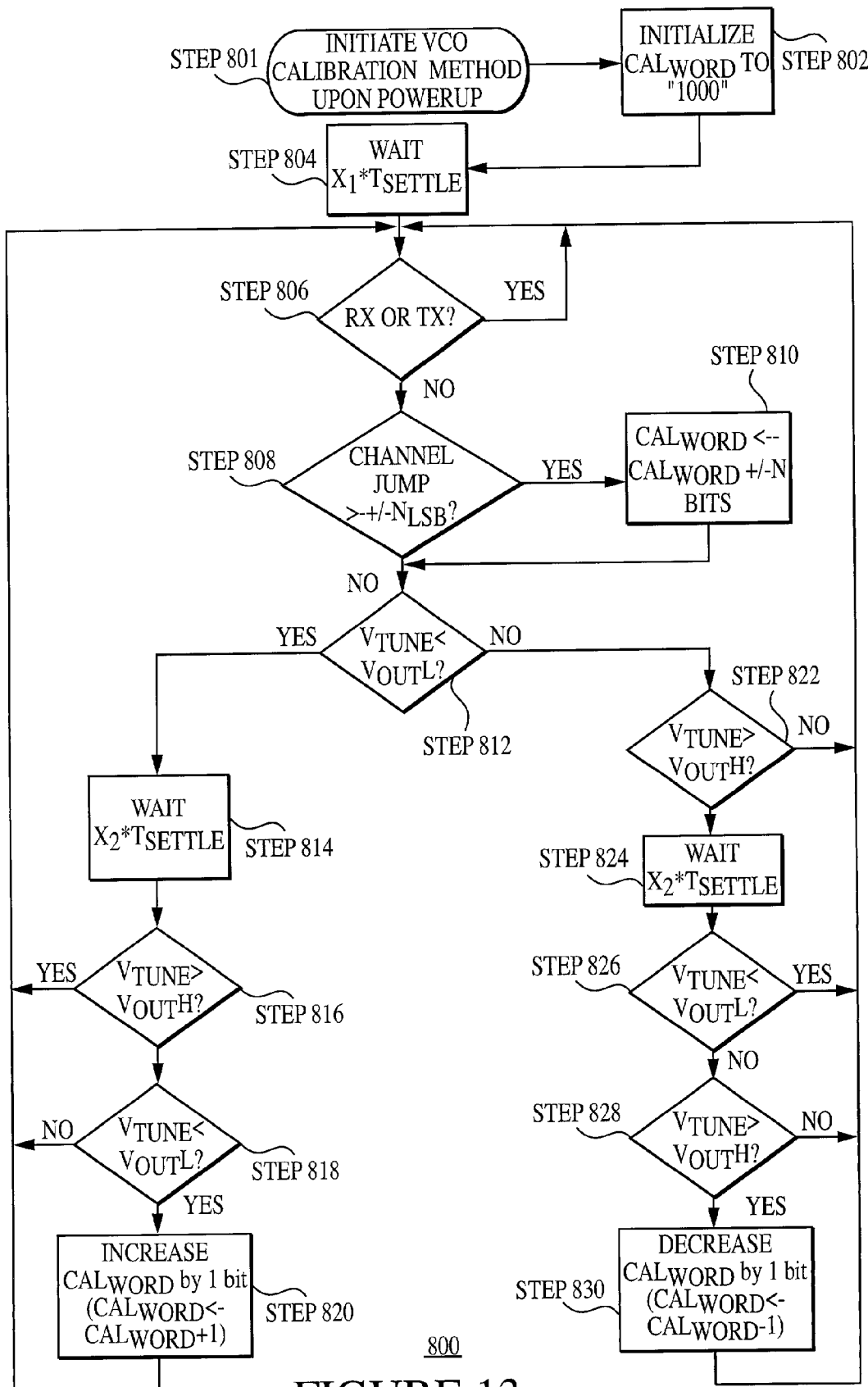ilm thickness, process uniformity and manufacturing equipment cleanliness, and other factors, integrated circuit passive electrical components often have tolerances that are approximately an order of magnitude worse than their analogous discrete external passive electrical components. Consequently, it has proven difficult and costly in the past to implement tuned networks or circuits using on-chip passive electrical components. One such tuned circuit is a voltage-controlled oscillator (VCO) in which a number of passive electrical devices are typically utilized to establish both the operating frequency and frequency offset of the VCO.

[0006] One well-known solution to this tolerance problem is to "trim" the integrated circuit until it operates within a set of pre-defined post-fabrication parameters. These "post-fabrication trimming" techniques are performed after manufacturing and testing the integrated circuit and are designed to physically alter the integrated circuit using a variety of methods including "Zener-zapping", laser trimming and fuse trimming. For example, using well-known fuse trimming techniques, fuseable links in an integrated circuit can be blown until the integrated circuit performs adequately under selected nominal conditions. Using these post-fabrication trimming techniques, passive electrical devices can be "fine-tuned" until they have acceptable tolerance values under nominal conditions. Disadvantageously, the trimming techniques produce only static solutions. For example, in fuse trimming, although the devices may perform adequately under nominal conditions, they may not perform adequately under all of the operating conditions of the integrated circuit. However, disadvantageously, the integrated circuit is permanently configured once the fuses are blown.

[0007] For example, as the voltage and temperature of the integrated circuit varies over time, offsets can be introduced despite the static settings created during the fuse trimming process. Devices that were once usable under the nominal conditions at which the fuses were blown may become unusable under some operating conditions, thus adversely affecting yield characteristics of the integrated circuits. In addition, the prior art post-fabrication solutions disadvantageously introduce additional manufacturing and testing steps into the manufacturing process. Using these prior art approaches, the manufacturer must first measure performance characteristics, trim the integrated circuits to conform to a selected set of performance and tolerance criteria, and test the results to ensure that the integrated circuit is trimmed appropriately. Thus, the prior art post-fabrication trimming techniques add additional time to the design and fabrication of integrated circuit devices and consequently add to the manufacturing costs of the integrated circuits.

[0008] Therefore, an improved method for improving the tolerances of passive electrical devices in an integrated circuit is needed which does not require the use of post-fabrication trimming techniques. Further, an improved method and apparatus is needed which dynamically monitors and corrects the performance characteristics of integrated circuits under all operating conditions. The improved method and apparatus should monitor and correct the performance characteristics of tuned networks especially as these performance characteristics are adversely affected by poor tolerances of on-chip passive electrical devices.

[0009] FIG. 1 shows a prior art attempt at solving the problem of implementing tuned circuits using on-chip passive electrical devices having poor or unacceptable tolerance values. As shown in FIG. 1, using an integrated switchable capacitor circuit 100, two terminals of an integrated tuned circuit (i.e., terminal A 101 and terminal B 103) can be selectively coupled to a bank of switchably connected capacitors (C_1 through C_n). Each of the capacitors is selectively coupled between the terminals 101, 103 by closing an associated and respective coupling switch S_n. For example, capacitor C_1 102 is coupled between the terminals 101, 103 by closing an associated switch S_1 110. Similarly, capacitor C_2 104 is coupled between the terminals 101, 103 by closing an associated switch S_2 112. Finally, capacitor C_n 108 is coupled between the terminals 101, 103 by closing an associated switch S_n 116. Because the individual capacitors are connected in a parallel configuration, the total capacitance between the terminals 101, 103 is equal to the sum of the individual capacitors that are switched into the circuit (assuming that the switches do not also introduce capacitance to the circuit). By electrically connecting the terminals 101, 103 to a tuned circuit that is on the same integrated circuit as the switchable capacitor circuit 100, the capacitors can be selectively switched in and out of the tuned circuit, thereby changing the capacitance between the terminals 101, 103 to a desired value. Thus, despite the poor tolerance characteristics of the capacitors C_1 through C_n, the tuned circuit can be adjusted to operate within desired parameters by simply changing the capacitance between terminals A 101 and B 103.

[0010] Disadvantageously, this prior art approach is undesirable when the tuned circuit operates at relatively high frequencies. For example, when the tuned circuit operates in the GHz range of operating frequencies, the bank of switches (e.g., 110, 112, 114, and 116) introduce significant loss into the tuned circuit and thereby degrade the circuit's

performance characteristics. The prior art solution shown in **FIG. 1** also disadvantageously increases both the amount of space (i.e., integrated circuit real estate) and the amount of power required to accommodate and operate the switches. Power requirements are increased due to the D.C. current required to operate the bank of switches.

[0011] Therefore, a need exists for a method and apparatus that can overcome the disadvantages associated with the prior art solutions and that will facilitate the integration of tuned capacitor networks on a single integrated circuit. The need exists for an apparatus that facilitates the full integration of a calibrated tuned capacitor network such as a voltage-controlled oscillator (VCO). In addition, the need exists for an apparatus and method that can dynamically calibrate an integrated tuned capacitor network such as a VCO. The present invention provides such a method and apparatus. The present method and apparatus uses a one-bit or "binary" capacitor formed from a MOSFET transistor that can be switched from a first pre-determined capacitance value to a second pre-determined capacitance value by varying an applied control voltage between first and second pre-determined voltage values. A multi-bit digital capacitor can be implemented by connecting a bank of the binary capacitors in parallel, and by weighting the individual capacitors as desired. The multi-bit digital capacitor allows capacitance values to be customized to any desired and convenient value.

SUMMARY OF THE INVENTION

[0012] The present invention is a novel apparatus comprising a one-bit or "binary" capacitor formed from a MOSFET integrated device that can be switched from a first pre-determined capacitance value C_1 to a second predetermined capacitance value C_2 by varying an applied control voltage between a first and a second pre-determined voltage value. An inventive multi-bit digital capacitor is implemented by connecting a bank of the binary capacitors in parallel, and by weighting the individual capacitors in a desired fashion. The multi-bit digital capacitor allows capacitance values within an integrated circuit device to be customized to any desired and convenient value.

[0013] The gate-to-bulk capacitance of the binary capacitor is dependent upon the D.C. voltage applied between the gate of the device and electrically coupled well contact implant regions. The capacitance-voltage characteristic of the binary capacitor has three major regions: (1) a first relatively flat region where there is little or no voltage dependency and where the capacitance equals a first low capacitance of C_1; (2) a sloped region wherein a voltage dependency exists; and (3) a second relatively flat region where there is little or no voltage dependency and where the capacitance equals a second higher capacitance of C_2. Simply changing the polarity of the applied D.C. voltage from a first value to a second value abruptly changes the capacitance of the binary capacitor from C1 to C2.

[0014] In accordance with one aspect of the present invention, a plurality of binary capacitors is arranged in a parallel configuration to produce a digitally controlled capacitor. Advantageously, the digitally controlled capacitor can be used in any integrated circuit that requires a tightly controlled tuned network. One such application is a voltage-controlled oscillator (VCO). In accordance with one aspect

of the present invention, the inventive digitally controlled capacitor is used in implementing a LC-resonator circuit, which is part of a fully integrated VCO device. The LC resonance frequency of the LC-resonator is varied by digitally modifying the capacitance of the LC tank circuit. The LC tank circuit is tuned with respect to an applied D.C. control voltage. Process variations introduced during the integrated circuit manufacturing process require that the LC-resonance frequency be re-centered after fabrication. In accordance with the present invention, the center output frequency of the VCO is calibrated by digitally modifying the capacitance of the VCO's digitally controlled capacitor. A means for determining whether the VCO requires calibration and a means for calibrating the center output frequency of the VCO is also presented.

[0015] Consequently, the inventive VCO can be implemented in an integrated circuit design despite poor tolerance values typically associated with process variations in integrated circuit fabrication. The present invention advantageously increases the effectiveness of integrated circuit VCO designs, tuning networks, and the like. The present invention improves the performance of wireless communication devices without requiring the use of expensive and large discrete components. The present invention is particularly useful in broadband wireless digital communication systems such as CDMA cellular systems, however it can also find utility in other communication systems such as those made in accordance with the proposed Bluetooth standard.

[0016] The details of the preferred and alternative embodiments of the present invention are set forth in the accompanying drawings and the description below. Once the details of the invention are known, numerous additional innovations and changes will become obvious to one skilled in the art.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] **FIG. 1** is a prior art attempt at solving the problem of implementing tuned circuits using on-chip passive electrical devices having poor or unacceptable tolerance values.

[0018] **FIG. 2** shows a simplified cross-sectional view of a MOSFET structure configured for use as a "binary" capacitor in accordance with the present invention.

[0019] **FIG. 3** is a capacitance-voltage (CV) plot showing the dependency of the gate-to-bulk capacitance $C_{gate\text{-}bulk}$ versus the D.C. bias voltage applied between the gate and the well of the binary capacitor shown in **FIG. 2**.

[0020] **FIG. 4**a is a simplified schematic showing the binary capacitor of **FIG. 2** configured for use as a digitally controlled multi-bit digital capacitor having a digitally selectable and variable capacitance.

[0021] **FIG. 4**b is a simplified schematic representation of the digital capacitor of **FIG. 4**a.

[0022] **FIG. 5** is a plot showing how the capacitance of the multi-bit digital capacitor of **FIG. 4**a varies depending upon the digital control word CAL_{word} applied to the terminals of the plurality of binary capacitors shown in **FIG. 4**a.

[0023] **FIG. 6** shows a differential mode implementation of the digital capacitor of **FIG. 4**a.

[0024] **FIG. 7** is a schematic of a simple differential LC-oscillator circuit.

[0025] **FIG. 8** shows a modified version of the LC-resonator circuit of **FIG. 7** wherein the digital capacitor of **FIG. 4***a* is connected in a parallel arrangement with an analog tuning varactor and a fixed LC-tank circuit capacitor.

[0026] **FIG. 9** is a schematic of a calibrating voltage-controlled oscillator (VCO) made in accordance with the present invention.

[0027] **FIG. 10** is a simplified schematic of the calibrating VCO of **FIG. 9** using a simplified schematic representation of the digital capacitor of the present invention.

[0028] **FIG. 11** is a simplified block diagram of a phase locked loop (PLL) circuit **600** using the VCO of **FIGS. 9 and 10**.

[0029] **FIG. 12** is a simplified block diagram demonstrating the principles of auto-calibration of the output center frequency of the inventive VCO of **FIGS. 9 and 10**.

[0030] **FIG. 13** shows a flowchart of one embodiment of a VCO center frequency auto-calibration method in accordance with the present invention.

[0031] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION OF THE INVENTION

[0032] Throughout this description, the preferred embodiment and examples shown should be considered as exemplars, rather than as limitations on the present invention.

[0033] **FIG. 2** shows a simplified cross-sectional view of a MOSFET structure configured for use as a "binary" capacitor in accordance with the present invention. As shown in **FIG. 2, a** binary capacitor **200** made in accordance with the present invention preferably comprises an N-well (or "bulk") **120**, N$^+$ well contact implant regions **122, 124**, metal well contacts **126, 128**, and a poly-silicon P-gate **130**. Using well-known MOSFET fabrication techniques, the binary capacitor **200** of the present invention is preferably formed by lightly doping the N-well implant layer **120** (for a p-channel MOSFET device) with appropriate n-type dopant materials. The N$^+$ well contact implant regions **122, 124** preferably comprise highly doped N$^+$ regions diffused into the N-well implant layer **120**. The metal area of the P-gate **130**, in conjunction with the insulating dielectric oxide layer and the semiconductor channel formed between the N$^+$ well contact implant regions **122, 124**, create a parallel-plate capacitor. The capacitor is formed between the P-gate **134** and the electrically coupled metal well contacts **126** and **128**. As described below in more detail with reference to **FIG. 3**, the capacitance between the P-gate **130** and the well **120** (the "gate-to-bulk" capacitance $C_{gate-bulk}$) of the binary capacitor **200** varies depending upon the D.C. bias voltage applied between the P-gate terminal **134** and the well contact implant terminals **132, 136**.

[0034] **FIG. 3** shows the dependency of the gate-to-bulk capacitance $C_{gate-bulk}$ upon the D.C. bias voltage that is applied between the P-gate terminal **134** and the well contact implant terminals **132, 136** of the binary capacitor **200** of **FIG. 2**. As shown in the capacitance-voltage plot of **FIG. 3**, the gate-to-bulk capacitance $C_{gate-bulk}$ varies between a first capacitance value C_{LOW} and a second capacitance value C_{HIGH} as the applied D.C. bias voltage is varied between a first

threshold voltage V_1 and a second voltage threshold V_2. In this embodiment of the binary capacitor **200** (i.e., a P-gate/N-well embodiment), V_1 and V_2 are applied to the P-gate terminal **134** with positive polarities with respect to the well contact terminals **132, 136**. That is, V_1 and V_2 are applied as positive polarity voltages with respect to the N$^+$ well contact implant regions **122, 124**. The binary capacitor **200** is said to be operating in an "accumulation" mode in this embodiment.

[0035] Referring again to **FIG. 3**, by applying a D.C. bias voltage $V_{applied}$ that is equal to or less than V_1, $C_{gate-bulk}$ (V)=C_{LOW}. By applying a positive D.C. bias voltage $V_{applied}$ that is equal to or greater than V_2, $C_{gate-bulk}$ (V)=C_{HIGH}. As the D.C. bias voltage varies between the threshold voltages V_1 and V_2, $C_{gate-bulk}$ (V) follows the slope as shown in **FIG. 3** and varies between the first capacitance value C_{LOW} and the second capacitance value C_{HIGH} (i.e., the binary capacitor **200** behaves as a varactor in this relatively narrow voltage range). Thus, as shown, the binary capacitor **200** of **FIG. 2** has a first lower capacitance C_{LOW} (that is flat over a relatively wide voltage range less than or equal to V_1), a second higher capacitance C_{HIGH} (that is flat over a relatively wide voltage range greater than or equal to V_2), and a variable capacitance (variable between C_{LOW} and C_{HIGH}) in the relatively narrow range of voltages between V_1 and V_2.

[0036] In one preferred embodiment of the binary capacitor, the second capacitance value C_{HIGH} is approximately two to three times greater than the first capacitance value C_{LOW}. That is, C_{HIGH}/C_{LOW} is approximately equal to 2 or 3 in one preferred embodiment. Simply varying the device geometry and thereby making the physical size of the capacitor larger or smaller can vary the specific values of C_{LOW} and C_{HIGH} for any specific binary capacitor.

[0037] By varying the D.C. bias voltage applied across the terminals (e.g., the terminals **132, 134, 136**) of the binary capacitor **200** of **FIG. 2**, the capacitance value is varied between C_{LOW} and C_{HIGH}. If V_1 represents a Boolean logic value of "zero", and V_2 represents a logical "one", then the capacitance $C_{gate-bulk}$ (V) can be digitally controlled using one control bit to be equal to either C_{LOW} (when a logical zero is applied) or C_{HIGH} (when a logical one is applied). Thus, the device shown in **FIG. 2** is referred to as a "binary" capacitor because the capacitance of the device **200** can be digitally controlled to be equal to one of two states. Specifically, the digital control signal controls the difference or differential between C_{HIGH} and C_{LOW} (referred to hereinafter as the "differential capacitance"). That is C_{LSB} (the differential capacitance of the binary capacitor **200** as controlled by a least significant bit of a digital control word) is equal to C_{HIGH} minus C_{LOW}.

[0038] Although one embodiment of the binary capacitor of the binary capacitor is shown in **FIG. 2**, other alternative embodiments are possible. As described above, the binary capacitor **200** may be implemented using a bulk CMOS process. Alternatively, the binary capacitor may be implemented as an integrated circuit varactor structure that includes a P-gate/N-well layer structure preferably formed on a Silicon-on-Insulator ("SOI") substrate. In this embodiment of the binary capacitor **200**, the varactor structure is completely isolated from the substrate of the integrated circuit by an oxide layer of the SOI substrate, and by

4

oxide-filled trenches formed on both sides of the varactor structure. The trenches preferably extend to the oxide layer of the SOI substrate. This alternative embodiment of the binary capacitor **200** is described more fully in commonly assigned U.S. Pat. No. 6,172,378, entitled "Integrated Circuit Varactor having a Wide Capacitance Range," issued on Jan. 9, 2001. This issued patent is incorporated by reference herein for its teachings of P-gate/N-well varactor structures.

[0039] In another preferred embodiment, the binary capacitor **200** may be implemented as an integrated circuit varactor structure that includes an N-gate/P-well structure formed on either an N-substrate bulk CMOS substrate or an SOI CMOS substrate. The N-gate/P-well embodiment of the binary capacitor is identical to the P-gate/N-well structure of **FIG. 2**, with the exception that the N-gate/P-well structure uses p-type dopant materials in the place of the n-type dopant materials used in the N-well device. More specifically, and referring again to **FIG. 2**, in a P-well implementation of the binary capacitor **200**, the well implant layer **120** is preferably lightly doped with appropriate p-type dopant materials. Similarly, the contact implant regions **122, 124** preferably comprise highly-doped P+ regions diffused into the P-well implant layer **120** in the preferred P-well implementation of the binary capacitor **200** of **FIG. 2**.

[0040] The capacitance of the P-well binary capacitor **200** is controlled by applying a D.C. bias voltage between the N-gate terminal **134** and the electrically coupled well contact terminals **132, 136** as described above with reference to the N-well device. However, in the P-well embodiment of the binary capacitor, V_1 and V_2 are applied to the N-gate terminal **134** as negative polarity voltages with respect to the P-well contact terminals **132, 136**. That is, V_1 and V_2 are applied as negative voltages with respect to the P^+ well contact implant regions **122** and **124**. In this embodiment the binary capacitor is said to be operating in a "depletion" mode.

[0041] As described above with reference to the N-well embodiment, by applying a negative polarity D.C. bias voltage $V_{applied}$ that is equal to or less than V_1 (i.e., in this embodiment, equal to or more positive than V_1), $C_{gate-bulk}$ (V) C_{LOW}. By applying a negative D.C. bias voltage $V_{applied}$ that is equal to or greater than V_2 (i.e., in this embodiment, equal to or more negative than V_2), $C_{gate-bulk}$ $(V)=C_{HIGH}$. As the D.C. bias voltage varies between the threshold voltages V_1 and V_2, $C_{gate-bulk}$ (V) varies between the first capacitance value C_{LOW} and the second capacitance value C_{HIGH} (i.e., the binary capacitor **200** behaves as a varactor in this relatively narrow voltage range).

[0042] Note that in this embodiment, the applied voltage $V_{applied}$ is increased to become more and more negative (e.g., from –0.5V to –1.5V) as it changes from the "low" threshold voltage of V_1 to the "high" threshold voltage V_2.

[0043] The N-gate/P-well integrated circuit varactor structure formed on an SOI substrate is described more fully in the incorporated U.S. Pat. No. 6,172,378. This issued patent is incorporated by reference herein for its teachings of N-gate/P-well varactor structures.

[0044] As described in more detail below with reference to FIGS. **4-10**, the present binary capacitor **200** of **FIG. 2** can be used as an integral building block in any integrated circuit that requires the use of passive components having

improved tolerances. For example, the binary capacitor **200** can be used to improve the performance of integrated circuit implementations of tuned capacitor networks such as voltage-controlled oscillators (VCO). Further, the binary capacitor **200** of the present invention can be used to implement a means of calibrating (both manually and automatically) a tuned capacitor network such as a VCO. Although the present binary capacitor **200** is described below with reference to its use in an integrated circuit implementation of a VCO, this specific use is exemplary only and should not be interpreted as limiting the scope or application of the present invention. Those skilled in the integrated circuit design and fabrication art will recognize that the binary capacitor **200** can be used to improve the performance of any integrated circuit requiring the use of passive electrical components.

[0045] **FIG. 4**a shows how the binary capacitor **200** described above with reference to **FIGS. 2 and 3** is used to create a digitally controlled or multi-bit digital capacitor **300** having a digitally selectable and variable capacitance. As shown in **FIG. 4**a, a plurality of binary capacitors are preferably connected in parallel between two terminals (i.e., between terminal A **301** and terminal B **303**) within an integrated circuit (not shown). The terminals A **301** and B **303** are analogous to the terminals A **101** and B **103** of **FIG. 1** and, as described in more detail below, may be connected to a tuned circuit such as a VCO. In accordance with the present invention, the capacitance values of the binary capacitors are preferably weighted in a convenient and desirable manner. For example, in the embodiment shown in **FIG. 4**a, the binary capacitors of the multi-bit digital capacitor **106** are given binary weighting. More specifically, the least-significant binary capacitor C_1 **302** is manufactured to have a desired least significant (or lowest) differential capacitance of C_{LSB} (defined as the difference between C_1's highest capacitance $C_{1\ HIGH}$ and C_1's lowest capacitance $C_{1\ LOW}$).

[0046] The next significant binary capacitor C_2 **304** is preferably manufactured to have a differential capacitance of twice C_{LSB}, or $2*C_{LSB}$. The binary weighting is assigned in like fashion with each next significant capacitor having a differential capacitance that is a power of two greater than the previous significant capacitor. Finally, the most significant binary capacitor C_n **306** is manufactured to have a differential capacitance of $2^{n-1}*C_{LSB}$. Those skilled in the IC manufacturing art will appreciate that several alternative means may be used to make the differential capacitance of a selected binary capacitor (for example, C_2) have a value that is a power of two greater than the previous significant capacitor (in this example, C_1). For example, in one embodiment, the selected capacitor (e.g., C_2) can be formed by placing two previous significant capacitors (in this example, C_1) in parallel. Similarly, the next significant capacitor (e.g., C3) can be formed by placing four of the previous significant capacitors (e.g., C_1) in parallel. Alternatively, the capacitors may be manufactured to different physical dimensions to have the desired differential capacitance characteristics.

[0047] In addition, although the binary capacitors of the embodiment shown in **FIG. 4**a are given a binary weighting, those skilled in the art will recognize that any convenient capacitance-weighting scheme can be assigned to the capacitors. For example, in an alternative embodiment where a logarithmic scaling is desired, each binary capacitor can be manufactured to have a capacitance value that is ten

times greater than its previous significant capacitor. More specifically, binary capacitor C_2 **304** can be manufactured to have a differential capacitance that is $10*C_{LSB}$, where C_1 **302** is manufactured to have a differential capacitance of C_{LSB}. In this embodiment, C_n is assigned a differential capacitance of $10^{n-1}*C_{LSB}$.

[0048] Referring again to **FIG. 4a**, the differential capacitance of each binary capacitor of the digital capacitor **106** is individually controlled by an associated and respective digital control signal that is applied over the terminals of the associated binary capacitor (i.e., by an associated and respective digital bit of a digital control word applied between the respective gate and well contact terminals). The control bits are ordered from least significant bit (LSB) to most significant bit (MSB), and are assigned to control the least significant capacitor to the most significant capacitor. Accordingly, the binary capacitors are ordered from least significant to most significant. For example, as shown in **FIG. 4a**, the least significant bit LSB, B_1 of the digital control word is preferably applied over the terminals of the least significant binary capacitor C_1 **302** and thereby controls the capacitance of the binary capacitor C_1 **302**. The next most significant bit, B_2, is applied to the terminals of the binary capacitor C_2 and thereby controls its capacitance. The most significant bit, B_n, similarly controls the capacitance of binary capacitor C_n.

[0049] As described above with reference to **FIGS. 2 and 3**, when B_1, for example, is a logical low value, or D.C. for example, the capacitance of binary capacitor C_1 **302** is equal to a first lower capacitance $C_{1\ LOW}$. Alternatively, when B_1 is a logical high value, or V_{cc} for example, the capacitance of the binary capacitor C_1 **302** is equal to a second higher capacitance $C_{1\ HIGH}$. The differential between $C_{1\ HIGH}$ and $C_{1\ LOW}$ is equal to C_{LSB}. Similarly, when B_2, for example, is a logical low value, or D.C., the capacitance of C_2 is equal to $C_{2\ LOW}$. When B_2 is a logical high value, or V_{cc}, the capacitance of binary capacitor C_2 is equal to $C_{2\ HIGH}$. Due to the binary weighting of C2, the differential capacitance of C2 (i.e., the difference between $C_{2\ HIGH}$ and $C_{2\ LOW}$) is equal to $2*C_{LSB}$. The trend continues as such, with each next significant binary capacitor having a differential capacitance that is twice the differential capacitance of its previous significant capacitor. Finally, as shown in **FIG. 4a**, the capacitance of binary capacitor C_n **306** varies between C_n LOW and C_n HIGH, as B_n varies between a logic low and logic high value. Again, due to the binary weighting of the capacitors the differential capacitance between C_n HIGH and C_n LOW is approximately equal to $2^{n-1}*C_{LSB}$.

[0050] Because the plurality of binary capacitors are connected together in a parallel configuration as shown in **FIG. 4a**, their respective capacitance values combine by simply adding the capacitance values of all of the individual binary capacitors. The capacitance of the digital capacitor **106** (as measured between the terminals A **301** and B **303**) is therefore equal to the sum of the capacitance of each of the binary capacitors C_n. **FIG. 4b** is a simplified schematic representation of the digital capacitor **106** shown in **FIG. 4a**.

[0051] **FIG. 5** shows a plot of the capacitance of the digital capacitor **106** as it varies depending upon the digital control word CAL_{word} **114** applied over the terminals of the plurality of binary capacitors. In the example shown, CAL_{word} is assumed to be three bits wide and therefore, in this embodiment, the number of binary capacitors used to implement the digital capacitor **106** is three. As shown in **FIG. 5**, the lowest capacitance value C_{FLOOR} is produced when the control word CAL_{word} **114** is set equal to all zeros (e.g., assuming a three-bit control word, n=3, CAL_{word}=000). Here, C_{FLOOR}=$C_{1\ LOW}$+$C_{2\ LOW}$+$C_{3\ LOW}$. The next higher capacitance value is produced using a control word CAL_{word} of "001". In this case, the capacitance of the digital capacitor **106** is equal to $C_{1\ HIGH}$+$C_{2\ LOW}$+$C_{3\ LOW}$, or C_{FLOOR}+C_{LSB}. By increasing the value of CAL_{word} by one to "010", the capacitance of the digital capacitor **106** is increased to the next step to a value of $C_{1\ LOW}$+$C_{2\ HIGH}$+$C_{3\ LOW}$, or C_{FLOOR}+$(2*C_{LSB})$. The digital control word CAL_{word} can be similarly incremented to produce the capacitance plot shown in **FIG. 5**. The capacitance of the digital capacitor **106** has its highest capacitance C_{MAX} equal to $C_{1\ HIGH}$+C_2 HIGH+C_3 HIGH when the digital control word CAL_{word} is set equal to "111". Stated in other terms, the highest capacitance C_{MAX} of the digital capacitor is C_{FLOOR} +$(7*C_{LSB})$.

[0052] **FIG. 6** shows a differential mode implementation of the digital capacitor **106** described above with reference to FIGS. 1-5. The digital capacitor **106** is preferably implemented differentially because this provides a convenient third terminal for digitally controlling the capacitance values of the binary capacitors. For example, as shown in **FIG. 6**, the control signal B_1 is applied between the binary capacitors C_1 **302, 302'** at a control terminal **310**. Similarly, the control signal B_2 is applied between the binary capacitors C_2 **304, 304'** at a control terminal **312**. The most significant control bit of the digital control word CAL_{word} **114**, B_n, is applied between the binary capacitors C_n, **306, 306'** at a control terminal **314**. The control terminals are common mode AC grounds.

[0053] The differential mode implementation of the digital capacitor **106** functions similarly to the digital capacitor **106** described above with reference to FIGS. 4-5. For example, the binary capacitors are preferably assigned a binary weighting, with the least significant capacitors C_1 **302, 302'** having the lowest differential capacitance (C_{LSB}). As shown in **FIG. 6**, the differential capacitance of the binary capacitors **302, 302'** is controlled at the control terminal **310** by the LSB of the digital control word CAL_{word}, i.e., by B_1. The differential capacitance of the next significant binary capacitors C_2 **304, 304'** is twice that of the least significant capacitors C_1, or $2*C_{LSB}$.

[0054] The capacitance of the binary capacitors C_2 **304, 304'** is similarly controlled at the control terminal **312** by the next most significant bit of the digital control word CAL_{word}, i.e., by B_2. The width of the control word CAL_{word} corresponds to the number of binary capacitor pairs used in the differential mode implementation of the digital capacitor **106**. The differential capacitance of the most significant binary capacitors is equal to $(2^{n-1}*C_{LSB})$. The MSB of the control word, i.e., B_n, controls the differential capacitance of the binary capacitors C_n **306, 306'**. Thus, the total capacitance of the differential mode implementation of the digital capacitor **106** is as follows:

$$C_{total}=C_{FLOOR}+B_1'C_{LSB}+B_2'(2*C_{LSB})+B_3'(4*C_{LSB})+\ .\ .\ .+B_n'* (2^{n-1}C_{LSB});$$

[0055] where the control word bits B_n' determine whether the differential capacitance of the nth capacitor (C_{LSB} or a multiple of C_{LSB} in the case when n is higher than 2) is or

is not added to C_{FLOOR}. More specifically, if B_n' is a logical zero, the differential capacitance of the $_n$th capacitor is not added (i.e., C_{LSB}, or its multiple, is not added to C_{FLOOR} for the $_n$th capacitor). If B_n' is a logical one, then the differential capacitance of C_{LSB} (or its multiple in the case of higher order bits) is added to C_{FLOOR} for the $_n$th capacitor.

[0056] Thus, by varying the value of the digital control word CAL_{word} 114 appropriately, and thereby varying the capacitance of each individual binary capacitor (i.e., binary capacitor C_1 302, C_2 304, . . . C_n 306), the capacitance of the digital capacitor 106 can be customized to any desired value. The step size shown in FIG. 5 (i.e., the resolution of the capacitance of the digital capacitor 106) depends upon the C_{LSB} of the capacitors. When the multi-bit digital capacitor 300 is used in implementing a tuned capacitor in an integrated circuit, the capacitance can be digitally calibrated as desired to meet pre-defined operational parameters.

[0057] Applications of the Multi-bit Digital Capacitor in an Integrated Circuit

[0058] The digital capacitor 300 of FIG. 4a and 300' of FIG. 6 can be used in place of the switched-capacitor circuit 100 of FIG. 1 to provide a calibrated capacitor for use in virtually any integrated circuit implementation of a tuned capacitor network. For example, consider the simple differential LC-oscillator circuit 400 shown in FIG. 7. The differential LC-oscillator 400 comprises an LC-resonator circuit 402, an amplifier 404, and a current source 405. As is well known in the electrical engineering art, the resonance frequency of the LC-resonator 402 defines the frequency of oscillation, or the center frequency, of the LC-oscillator 400 and is determined by the values of L and C. More specifically, the oscillation frequency, $f_o = 1/(2\pi * SQRT(L * C_{tot}))$.

[0059] Disadvantageously, if any of the integrated circuit components used to implement the LC-resonator 402 have poor tolerance values due to process variations or other factors, the oscillation frequency f_o will be adversely affected. This is particularly disadvantageous when the oscillation frequency is relatively high, for example, when the oscillation frequency operates in the Gigahertz range. At such high frequencies, the tolerance variations of the passive electrical components will dramatically affect variations in the oscillation frequency. For example, with a desired oscillation frequency of 2 GHz, a ±10% tolerance will yield an oscillation frequency of 2 GHz±200 MHz. This may be unacceptable in some applications. In addition, in order to obtain desired performance characteristics such as low phase noise and low power dissipation, the components of the LC-oscillator 400 (i.e., the L and C components) should have low series losses (i.e., the components should have high "Q" gain values).

[0060] A modified version 402' of the LC-resonator 402 of FIG. 7 is shown in FIG. 8. The digital capacitor C_{CAL} 300 described above with reference to FIGS. 4a and 4b is connected in a parallel arrangement with an analog tuning varactor 406 and a fixed LC-tank circuit capacitor C_L 408 as shown. As described above with reference to the LC-oscillator 400 of FIG. 7, the resonance frequency of the LC-resonator 402' of FIG. 8 is determined by the values of L and C_{total}. More specifically, the oscillation frequency, $f_o = 1/(2\pi * SQRT(L * C_{total}))$. The value of L remains fixed. Because the digital capacitor 300, the tuning varactor 406, and the fixed capacitor C_L 408 are connected in parallel,

their capacitance values add together to yield a total capacitance C_{total} of the LC-resonator 402. That is, $C_{total} = C_{CAL} + C_{tune} + C_L$.

[0061] The capacitance C_L 408 is a fixed and known pre-determined value. The capacitance C_{tune} is determined by applying a D.C. control voltage V_{tune} 410 to the tuning varactor 406. In practice, C_{tune} is tuned so that the oscillation frequency f_o is nominally equal to a desired center frequency, for example, 2 GHz. However, as described above, in order to compensate for fabrication process variations and other factors, the resonance or oscillation frequency f_o may require calibration in order to re-center the LC-resonance frequency to a desired center frequency value. The digital capacitor C_{CAL} 300 is used for this purpose. By applying an appropriate digital control word CAL_{word} 412 to the digital capacitor 300, the capacitance of the digital capacitor is changed to a desired value, and the center frequency of the LC-resonator 402' is thereby changed accordingly. The oscillation frequency f_o is therefore calibrated and re-centered by appropriately adjusting the digital control word CAL_{word}. Calibration of the LC-resonator 402' oscillation frequency f_o can be performed using either manual or automatic methods of calibration.

[0062] For example, in one embodiment, the LC-resonator 402' is manually calibrated by first measuring the oscillation frequency f_o during a production testing phase of the integrated circuit fabrication process. In this embodiment, the circuit is tuned to a desired oscillation frequency and the actual output frequency is measured. If the desired oscillation frequency differs from the measured output frequency the digital control word CAL_{word} is modified until the output frequency equals the desired oscillation frequency. The calibration control word thereby determined for CAL_{word} may then be stored in a non-volatile memory either within the same integrated circuit as the resonator or on a printed circuit board adjacent the integrated circuit. In another embodiment, the oscillation frequency f_o is automatically calibrated until a desired oscillation frequency is obtained.

[0063] Such an automatic calibration method may be executed every time the circuit is powered on. In one preferred embodiment, the automatic calibration method is executed by a microprocessor or other data processing device located within the integrated circuit or on the same printed circuit board as the integrated circuit. Alternatively, the method can be implemented using any convenient or desirable sequencing device such as a state machine, present state-next state discrete logic, or field programmable gate array device. A more detailed description of the auto-calibration method is described in more detail below together with a description of a self-calibrating VCO made in accordance with the present invention.

[0064] Use of the Digital Capacitor in Implementing a VCO in an Integrated Circuit

[0065] FIG. 9 shows a schematic of a voltage-controlled oscillator (VCO) made in accordance with the present invention. The VCO 500 shown in FIG. 9 uses both the differential mode implementation of the digital capacitor 300' of FIG. 6 and a differential mode implementation of the LC-resonator 402'' of FIG. 8 to produce a VCO that can be calibrated to generate a desired output frequency f_o based upon a given control voltage and given digital control word. As shown in FIG. 9, one preferred embodiment of the

7

calibrating VCO **500** of the present invention comprises two inductors L **502, 504**, the differential mode digital capacitor **300'** described in more detail above with reference to **FIG. 6**, an amplifier **404'**, and a current source **405**. The amplifier **404'** functions similarly to the amplifier **404** of **FIG. 7**. Similarly, the binary capacitors (e.g., the LSB binary capacitor C_1 **302, 302'**, next-significant binary capacitor C_2 **304, 304'**, and MSB binary capacitor C_4 **306, 306'**) function similarly to their respective and corresponding binary capacitors described above with reference to the differential mode digital capacitor of **FIG. 6**.

[0066] In the VCO of **FIG. 9**, the capacitance of the binary capacitors are controlled by a digital control word (comprising $VC_{1\ (LSB)}$, VC_2, VC_3, and $VC_{4\ (MSB)}$) that is buffered by associated and corresponding buffers **506**. **FIG. 10** is a simplified schematic of the calibrating VCO **500** of **FIG. 9** using the simplified schematic representation of the digital capacitor **300'**. Similar to the operation of the LC-resonator **402'** of **FIG. 8**, the oscillation or output frequency f_o of the VCO **500** is established by appropriately adjusting the analog tuning voltage V_{tune} **410** to a desired D.C. voltage level. Fabrication process variations can be compensated and the oscillation frequency f_o can be calibrated and re-centered by thereafter varying the digital control word CAL_{word} and thereby adjusting the capacitance of the digital capacitor **300'**. Advantageously, despite process variations in the fabrication of integrated circuits, the inventive VCO **500** of **FIGS. 9 and 10** allows circuit designers to accurately control the center frequency of the integrated circuit VCO. This is essential in some applications, especially when the VCO operates at relatively high frequencies.

[0067] In addition, given a set of tunable frequency ranges, the present invention provides a VCO having much lower gain and sensitivity characteristics than prior art VCO designs. Owing to the calibration function provided by the digital capacitor **300'**, the calibrating VCO **500** need be tunable only over a relatively narrow frequency range (i.e., the VCO only has to cover the frequency band of interest) as compared with the prior art VCO designs. Therefore, the present inventive VCO **500** is much less sensitive to noise than are the prior art VCO designs. The present VCO **500** performs better and is easier to implement that its prior art counterparts because it is less sensitive to low frequency noise and the deleterious effects of interfering RF signals.

[0068] **FIG. 11** is a simplified block diagram of a phase locked loop (PLL) circuit **600** that uses the VCO **500** described above with reference to **FIGS. 9 and 10**. As shown in **FIG. 11** the preferred embodiment of the PLL **600** comprises a multiplier or phase error detector **602**, a loop filter **604**, the VCO **500**, and a divide-by-M circuit **606**. The PLL **600** functions in a well-known manner to generate an output frequency f_o that is locked in phase with a precision reference signal f_r. The PLL **600** is a negative feedback system. The reference signal f_r and the output of the divide-by-M circuit **606** are applied to the inputs of the multiplier **602** as shown in **FIG. 11**. The multiplier **602** produces both a high frequency and a low-frequency component.

[0069] The high frequency component is eliminated by the combination of the loop filter **604** and the VCO **500**. The low frequency component output by the multiplier **602** contains information related to the phase error or difference in phase between the reference signal f_r and the divided down output

signal f_o (i.e., the output of the VCO **500** as divided-down by the divide-by-M circuit **606**). This phase error signal is filtered and used (as the tuning voltage V_{tune}) to control the frequency produced by the VCO **500**. The output signal generated by the VCO **500** is fed back to the divide-by-M circuit **606** thereby closing the PLL negative feedback loop.

[0070] When the phase error produced at the output of the multiplier **602** is zero, the PLL **600** is in a phase-lock condition. The VCO output signal f_o is a multiple of the reference signal f_r, specifically $f_o = M * f_r$. Due to the negative feedback operation of the PLL **600** described above, the output signal f_o tracks or follows the reference signal f_r. In the embodiment shown in **FIG. 11**, the reference frequency f_r is maintained at a desirable base frequency, while the output center frequency f_o is varied by varying the value of "M" in the divide-by-M circuit **606** (i.e., M can be assigned the values of M_1, M_2, M_3, etc., with each M-value having an associated and corresponding output center frequency f_{o1}, f_{o2}, f_{o3}, etc.).

[0071] When the VCO **500** is used in a radio communication system designed in accordance with the proposed "Bluetooth" standard, the VCO **500** must be capable of generating output signals having a frequency range of at least 78 MHz (i.e., the tunable range of the VCO must be at least 78 MHz), starting at 2.402 GHz and stopping at 2.48 GHz. Spectrum spreading in Bluetooth is accomplished in 79 frequency channel hops displaced by 1 MHz per frequency channel. The VCO **500** must therefore be capable of generating output signals corresponding to the transmit and receive frequency channels used in Bluetooth. However, it is desirable to reduce the gain of the VCO in order to reduce sensitivity to low-frequency noise signals. In one embodiment, the gain of the VCO **500** is approximately 50 MHz and the maximum tunable range of the VCO **500** is 300 MHz. In this embodiment, f_r is maintained at a base frequency of approximately 1 MHz. By changing the value of M in the divide-by-M circuit **606**, the VCO **500** generates multiple output channels separated by the 1 MHz reference frequency. More specifically, in an embodiment designed for use in a Bluetooth system, the output frequency varies between 2.402 GHz and 2.48 GHz at a 1 MHz channel spacing.

[0072] However, those skilled in the art will recognize that the VCO **500** of the present invention can be modified for use in a wide variety of applications without departing from the scope of the claims. For example, the tuning range and the output frequency channels generated by the inventive VCO **500** can be modified for use in a wideband communication system simply by changing the reference frequency, the value of M in the divide-by-M circuit **606**, and the value of CAL_{word}. In one wideband communication system contemplated for use with the present inventive VCO **500**, the VCO tuning range is approximately 300 MHz and the frequency channels are separated by approximately 16 MHz-wide steps. The inventive VCO **500** can also be used in applications such as use in implementing tunable filters.

[0073] Automatic Calibration of the VCO Center Frequency f_o

[0074] In one embodiment of the present invention, the output center frequency f_o generated by the VCO **500** is automatically calibrated to fall approximately in the center of the VCO tuning range (i.e., centered between the mini-

mum and maximum values of the tuning voltage V_{tune} that is applied to the control input of the VCO **500**). **FIG. 12** shows a simplified block diagram that demonstrates the principles of auto-calibration of the VCO center frequency. As shown in **FIG. 12**, the VCO **500** generates an output frequency f_o that is input to the phase locked loop circuit **600** described above with reference to **FIG. 11**. The PLL **600** performs a frequency-to-voltage conversion function whereby the output frequency f_o is compared with a reference frequency f_r to generate the tuning voltage V_{tune}. The tuning voltage V_{tune} is subsequently compared by a comparator **702** with a reference or threshold voltage V_{ref} as shown in **FIG. 12**. The total capacitance of the LC-resonator circuit (**FIG. 8**) within the VCO **500** is modified based upon the comparison of the tuning voltage V_{tune} with the reference or threshold voltage V_{ref}. This voltage-to-capacitance function is performed by the digital capacitor circuit **300**, and specifically by updating the digital control word CAL_{word}. Thus, by periodically monitoring the input tuning voltage V_{tune}, and by comparing the tuning voltage to a threshold voltage, the VCO output center frequency can be automatically calibrated.

[0075] **FIG. 13** shows a flowchart of one embodiment of a VCO center frequency auto-calibration method **800** in accordance with the present invention. In one embodiment of the present invention, the method **800** shown in **FIG. 13** is implemented in software instructions that are executed by a micro-processor, state machine, or other digital logic device operatively coupled to the inventive VCO **500**. However, those skilled in the digital control art will recognize that the method **800** may also be implemented in hardware, or by use of discrete logic circuits. As shown in **FIG. 13**, the VCO auto-calibration method **800** is initiated at STEP **801** when the VCO **500** is first powered on (i.e., after the VCO **500** enters a "powerup" state). The method **800** proceeds to a STEP **802** whereat the digital control word CAL_{word} is initialized to a pre-determined value. In the embodiment shown in **FIG. 13**, CAL_{word} is initialized to a value that is halfway between its maximum number (binary "1111") and its minimum number (binary "0000"), that is, CAL_{word} is set to a binary "**1000**". **The inventive VCO auto-calibration method 800 then proceeds to a waiting STEP 804 whereat the method waits for a pre-determined "settling" period of time.**

[0076] The method waits for the pre-determined "settling" period (shown as a scaling factor X_1 multiplied by a settling time T_{settle}) in order to allow the VCO **500** and the PLL **600** (**FIG. 11**) to settle after the powerup condition and to thereafter establish a nominal output frequency. The settling time can be determined experimentally and adjusted to meet the needs of specific VCO designs. In the embodiment shown in **FIG. 13**, after waiting the pre-determined settling period, the method **800** proceeds to a STEP **806** whereat a decision is made as to whether the radio system utilizing the VCO **500** is operating within a receive or transmit time slot. One preferred application for the present inventive VCO **500** is use in a frequency hop transceiver capable of generating receive and transmit frequencies in a wireless Time-Division Duplex scheme. One exemplary application of the inventive VCO **500** is in a radio system designed according to the proposed Bluetooth standard. When the VCO **500** is used in such a system the method **800** preferably prevents calibration of the VCO during the time slots that voice/data is being received or transmitted (i.e., during the Rx and Tx time

slots). Accordingly, as shown in **FIG. 13**, if the VCO is currently operating in a receive/transmit time slot, the decision STEP **806** "yes" output will be followed and the VCO **500** will not be calibrated. The method **800** will continue to loop back to the decision STEP **806** until the VCO is no longer operating in a receive/transmit time slot.

[0077] When the receive/transmit time slot is no longer active, the method proceeds to a decision STEP **808** and determines whether a "channel jump" or "channel hop" condition exits. In a communication system designed according to the proposed Bluetooth standard as described above, certain time slots are dedicated for frequency or channel "hopping." Consequently, when the inventive auto-calibration method **800** determines that a channel hop has occurred in the STEP **808**, and that the channel frequency change or channel hop delta is greater than a pre-determined threshold, the method preferably proceeds to a STEP **810** and updates the digital control word CAL_{word} to reflect the corresponding change in output frequency. More specifically, in the embodiment shown in **FIG. 13**, a determination is made at the decision STEP **808** as to whether the channel frequency was increased or decreased by a factor of n*LSB; wherein n is an integer and "LSB" is a pre-defined frequency resolution determined by the least significant bit of the digital control word CAL_{word}.

[0078] For example, in one embodiment of the present invention, one LSB of the digital control word CAL_{word} changes the VCO **500** output frequency f_o by 30 MHz. In such an embodiment, if the channel jump detected in STEP **808** is greater than or equal to 30 MHz (i.e., greater than plus or minus 1 LSB), then CAL_{word} is updated accordingly at STEP **810** to change the center frequency of the VCO **500**. Similarly, if the channel jump is greater than 60 MHz (i.e., greater than plus or minus 2 LSB), the CAL_{word} is updated in STEP **810** to change the center frequency f_o of the VCO by 60 MHz. Those skilled in the VCO art will appreciate that the STEPS **806**, **808** and **810** can be eliminated when the VCO is not designed for use in a Time-Division Duplex wireless communication system having frequency or channel hopping. For more general use, the method **800** of **FIG. 13** proceeds directly from the waiting STEP **804** to a decision STEP **812**.

[0079] The remainder of the inventive VCO auto-calibration method monitors the VCO analog tuning voltage V_{tune} and determines whether the VCO output frequency f_o requires calibration. For example, at the decision STEP **812**, the method determines whether the analog tuning voltage V_{tune} is less than a pre-determined V_{out} "low threshold" value "$V_{out}L$." In some situations, especially when the VCO **500** is first powered on, the PLL **600** can become locked into a condition wherein the output frequency f_o is saturated to a given high frequency, and the analog tuning voltage becomes locked below a low threshold voltage of $V_{out}L$. In this scenario, the method will modify the digital control word CAL_{word} and thereby decrease the output frequency f_o generated by the VCO **500**. The method will increase the digital control word CAL_{word} to thereby decrease the output frequency, which, due to the negative feedback of the PLL **600**, will, in turn, increase the analog tuning voltage V_{tune}.

[0080] If the method determines at STEP **812** that the analog tuning voltage V_{tune} is greater than the low threshold value $V_{out}L$, then the method proceeds to a decision STEP

822 whereat it determines whether the analog tuning voltage V_{tune} is greater than a pre-determined V_{out} "high threshold" value "$V_{out}H$." As described above, in some situations, especially when the VCO **500** is first powered on, the PLL **600** can become locked into a condition wherein the output frequency f_o is saturated to a given low frequency, and the analog tuning voltage becomes locked above a high threshold voltage $V_{out}H$. In this scenario, the method will modify the digital control word CAL_{word} and thereby modify the output frequency f_o generated by the VCO **500**. The method will decrease the digital control word CAL_{word} and thereby increase the output frequency, which, due to the negative feedback of the PLL **600**, will decrease the analog tuning voltage V_{tune}. The remainder of the method **800** is now described in more detail.

[0081] If a determination is made at the decision STEP **812** that V_{tune} is less than the pre-determined low threshold voltage $V_{out}L$ (i.e., the outcome of the decision step is "yes"), the method proceeds to a waiting STEP **814** and waits for a pre-determined period of time for the output frequency of the VCO to settle. For example, as shown in **FIG. 13**, at the STEP **814** the method waits for a time period equal to a scaling factor "X_2" multiplied by a pre-defined settling time T_{settle} to allow the VCO **500** to settle. In one embodiment of the present invention, the waiting time provided by STEP **814** is approximately 100 microseconds. However, those skilled in the VCO design art shall recognize that both the scaling factor X_2 and the settling time T_{settle} can be modified to accommodate various VCO designs without departing from the scope of the present invention.

[0082] The method **800** waits during the waiting STEP **814** to determine whether the tuning voltage V_{tune} is still less than the low threshold voltage $V_{out}L$, and therefore whether the VCO still requires calibration. The method proceeds from the STEP **814** to a decision STEP **816** to determine whether the analog tuning voltage V_{tune} is greater than the pre-defined high threshold $V_{out}H$. If V_{tune} is greater than $V_{out}H$, the method returns to the STEP **806** and proceeds as described above. However, if V_{tune} is less than $V_{out}H$ the method proceeds to decision STEP **818** to once again determine if the analog tuning voltage V_{tune} is less than the low threshold $V_{out}L$. If not, there is no reason to calibrate the VCO **500**, and the method returns to the STEP **806** and proceeds as described above. However, if V_{tune} is still less than the low threshold voltage $V_{out}L$, the method proceeds to the STEP **820** to calibrate the VCO **500**. As shown in **FIG. 13**, calibration of the VCO **500** is preferably accomplished by modifying the digital control word CAL_{word}. In this case, calibration is accomplished by increasing CAL_{word} by one bit (i.e., $CAL_{word} < -CAL_{word}+1$). Increasing CAL_{word} by one bit causes the VCO output frequency to decrease, which, due to the negative-feedback operation of the PLL **600**, causes the tuning voltage V_{tune} to increase. The method then returns to the STEP **806** to determine whether further calibration is required.

[0083] The right side of the flowchart shown in **FIG. 13** operates in a similar manner to decrease CAL_{word} when the analog tuning voltage V_{tune} is determined to be greater than a pre-defined high threshold voltage $V_{out}H$. Specifically, the method **800** waits during a STEP **824** to determine whether the tuning voltage V_{tune} is still greater than the high threshold voltage $V_{out}H$, and therefore whether the VCO still requires calibration. The method proceeds from the STEP

824 to a decision STEP **826** to determine whether the analog tuning voltage V_{tune} is less than the pre-defined low threshold $V_{out}L$. If V_{tune} is less than $V_{out}L$, the method returns to the STEP **806** and proceeds as described above. However, if V_{tune} is greater than $V_{out}L$, the method proceeds to a decision STEP **828** to once again determine if the analog tuning voltage V_{tune} is greater than the high threshold voltage $V_{out}H$. If not, there is no reason to calibrate the VCO **500**, and the method returns to the STEP **806** and proceeds as described above. However, if V_{tune} is still greater than the high threshold voltage $V_{out}H$, the method proceeds to the STEP **830** to calibrate the VCO **500**. As described above, calibration of the VCO **500** is accomplished by modifying the digital control word CAL_{word}. In this case, calibration is accomplished by decreasing CAL_{word} by one bit (i.e., $CAL_{word} < -CAL_{word}-1$). Decreasing CAL_{word} by one bit causes the VCO output frequency to increase, which, due to the negative-feedback operation of the PLL **600**, causes the tuning voltage V_{tune} to decrease. The method then returns to the STEP **806** to determine whether further calibration is required.

SUMMARY

[0084] In summary, the invention includes a digital or binary capacitor comprised of a MOSFET device wherein the gate-to-bulk capacitance of the MOS-FET device exhibits dependency to the D.C. voltage applied between its gate and well implant regions. The capacitance-voltage characteristic of the binary capacitor has three major regions: (1) a first relatively flat region where there is little or no voltage dependency and where the capacitance equals a first low capacitance of C_1; (2) a sloped region wherein a voltage dependency exists; and (3) a second relatively flat region where there is little or no voltage dependency and where the capacitance equals a second higher capacitance of C_2. The capacitance of the binary capacitor can be changed from C_1 to C_2 simply by changing the polarity of the applied D.C. voltage from a positive to a negative value.

[0085] A plurality of binary capacitors are configured in a parallel arrangement to produce a digitally-controlled capacitor. The digitally-controlled capacitor can be used in any integrated circuit requiring a tightly controlled tuned network. One application is a voltage-controlled oscillator (VCO) wherein the center output frequency of the VCO is calibrated by digitally modifying the capacitance of the VCO's digitally controlled capacitor. A means for determining whether the VCO requires calibration and a means for calibrating the center output frequency of the VCO is presented. Consequently, the inventive VCO can be implemented in an integrated circuit design despite poor tolerance values typically associated with process variations in integrated circuit fabrication. The present invention advantageously increases the effectiveness of integrated VCO designs, tuning networks, and the like. The present invention improves the performance of wireless communication devices without requiring the use of expensive and large discrete components. The present invention is particularly useful in broadband wireless digital communication systems such as CDMA cellular systems, however it can also find utility in other digital cellular communication systems such as those made in accordance with the proposed Bluetooth standard.

[0086] A number of embodiments of the present invention have been described. Nevertheless, it will be understood that

various modifications may be made without departing from the spirit and scope of the claimed invention.

[0087] Accordingly, it is to be understood that the invention is not to be limited by the specific illustrated embodiment, but only by the scope of the appended claims.

What is claimed is:

1. A method of calibrating a frequency adjustable oscillator circuit in an integrated circuit device, wherein the frequency adjustable oscillator circuit includes an inductor coupled in parallel to a plurality of multiple capacitance level capacitors, each multiple capacitance level capacitor having a plurality of steady-state capacitance levels, and wherein each multiple capacitance level capacitor is coupled to an associated and corresponding control signal, and wherein the capacitance level measured across the plurality of capacitors varies as a function of the corresponding control signal, the method comprising the steps of:

  a) tuning the oscillator circuit to a desired center frequency;

  b) measuring an actual center frequency generated by the oscillator circuit;

  c) comparing the actual center frequency measured in step (b) to the desired center frequency; and

  d) varying the control signals applied to the plurality of multiple capacitance level capacitors until the actual center frequency measured in step (b) is approximately equal to the desired center frequency of the oscillator circuit.

2. The method of calibrating a frequency adjustable oscillator as set forth in claim 1, wherein the tuning step (a) comprises the step of applying a DC control voltage (V_{tune}) to a tuning varactor coupled in parallel to the plurality of multiple capacitance level capacitors.

3. The method of calibrating a frequency adjustable oscillator as set forth in claim 1, wherein the measuring step (b), comparing step (c), and varying step (d) are manually performed during a production testing phase, and wherein the control signals are manually varied in step (d) until the actual measured center frequency is approximately equal to the desired center frequency of the oscillator.

4. The method of calibrating a frequency adjustable oscillator as set forth in claim 3, wherein the control signals are stored in a non-volatile memory device and subsequently used to calibrate the oscillator circuit.

5. The method of calibrating a frequency adjustable oscillator as set forth in claim 1, wherein the measuring step (b), comparing step (c), and varying step (d) are automatically performed when power is first supplied to the oscillator.

6. The method of calibrating a frequency adjustable oscillator as set forth in claim 5, wherein the control signals are controlled by a microprocessor.

7. The method of calibrating a frequency adjustable oscillator as set forth in claim 5, wherein the control signals are controlled by a field programmable gate array device.

8. A calibrating frequency adjustable oscillator circuit in an integrated circuit device, wherein the frequency adjustable oscillator circuit includes an inductor coupled in parallel to a plurality of multiple capacitance level capacitors, each multiple capacitance level capacitor having a plurality of steady-state capacitance levels, and wherein each mul-

tiple capacitance level capacitor is coupled to an associated and corresponding control signal, and wherein the capacitance level measured across the plurality of capacitors varies as a function of the corresponding control signal, the oscillator circuit comprising:

  a) means for tuning the oscillator circuit to a desired center frequency;

  b) means, coupled to the oscillator circuit, for measuring an actual center frequency generated by the oscillator circuit;

  c) means, coupled to the measuring means, for comparing the actual center frequency to the desired center frequency; and

  d) means, responsive to the comparing means, for varying the control signals applied to the plurality of multiple capacitance level capacitors until the actual center frequency is approximately equal to the desired center frequency of the oscillator circuit.

9. A method of automatically calibrating a voltage controlled oscillator (VCO) in an integrated circuit device, wherein the VCO includes at least one tuning varactor coupled in parallel to at least one inductor, and wherein the at least one inductor is coupled in parallel to a plurality of multiple capacitance level capacitors, each multiple capacitance level capacitor having a plurality of steady-state capacitance levels, and wherein each multiple capacitance level capacitor is coupled to an associated and corresponding control signal, and wherein the capacitance level measured across the plurality of capacitors varies as a function of the corresponding control signal, and wherein the control signals together comprise a control word, the method comprising the steps of:

  a) tuning the VCO to a desired center frequency;

  b) measuring an output frequency generated by the VCO;

  c) comparing the VCO output frequency measured in step (b) to the desired center frequency; and

  d) varying the control word applied to the plurality of multiple capacitance level capacitors until the VCO output frequency measured in step (b) is approximately equal to the desired center frequency.

10. The automatic VCO calibration method as set forth in claim 9, wherein the tuning step (a) comprises the step of applying a DC control voltage (V_{tune}) to a tuning varactor coupled in parallel to the plurality of multiple capacitance level capacitors.

11. The automatic VCO calibration method as set forth in claim 9, wherein the measuring step (b) is performed by a phase-locked loop circuit coupled to receive the VCO output frequency.

12. The automatic VCO calibration method as set forth in claim 11, wherein the VCO output frequency is compared with a reference frequency, and wherein the control word applied to the plurality of multiple capacitance level capacitors is varied responsive to the comparison.

13. A calibrating voltage controlled oscillator (VCO) in an integrated circuit device, wherein the VCO includes at least one tuning varactor coupled in parallel to at least one inductor, and wherein the at least one inductor is coupled in parallel to a plurality of multiple capacitance level capacitors, each multiple capacitance level capacitor having a

plurality of steady-state capacitance levels, and wherein each multiple capacitance level capacitor is coupled to an associated and corresponding control signal, and wherein the capacitance level measured across the plurality of capacitors varies as a function of the corresponding control signal, and wherein the control signals together comprise a control word, the VCO comprising:

    a) means for tuning the VCO to a desired center frequency;

    b) means, coupled to the VCO, for measuring an output frequency generated by the VCO;

    c) means, coupled to the measuring means, for comparing the VCO output frequency to the desired center frequency; and

    d) means, responsive to the comparing means, for varying the control word applied to the plurality of multiple capacitance level capacitors until the VCO output frequency is approximately equal to the desired center frequency.

    14. A self-calibrating voltage controlled oscillator (VCO), wherein the self-calibrating VCO is capable of being calibrated to produce a desired output frequency f_o based upon a selected tuning voltage and a selected digital control word, the VCO comprising:

    a) at least one inductor;

    b) a tuning varactor coupled to the at least one inductor, wherein the capacitance of the tuning varactor is controlled by a selected tuning voltage (V_{tune});

    c) a plurality of multiple capacitance level capacitors coupled in parallel to the tuning varactor, each multiple capacitance level capacitor having a plurality of steady-state capacitance levels, wherein each multiple capacitance level capacitor is coupled to an associated and corresponding control signal, and wherein the capacitance level measured across the plurality of capacitors varies as a function of the corresponding control signal, and wherein the control signals together comprise a digital control word;

    d) an amplifier coupled to the at least one inductor; and

    e) a current source coupled in serial to the amplifier;

    and wherein the digital control word applied to the plurality of multiple capacitance level capacitors is dynamically varied until the output frequency of the VCO is approximately equal to the desired output frequency.

    15. A self-calibrating voltage controlled oscillator (VCO), wherein the self-calibrating VCO is capable of being calibrated to produce a desired output frequency f_o based upon a selected tuning voltage and a selected digital control word, the VCO comprising:

    a) at least one inductor means;

    b) means for tuning the VCO to an initial output frequency, wherein the tuning means is controlled by a selected tuning voltage (V_{tune});

    c) means, for digitally controlling a plurality of multiple capacitance level capacitors coupled in parallel to the tuning means, each multiple capacitance level capacitor having a plurality of steady-state capacitance levels,

wherein each multiple capacitance level capacitor is coupled to an associated and corresponding digital control signal, and wherein the capacitance level measured across the plurality of capacitors varies as a function of the corresponding control signal, and wherein the control signals together comprise a digital control word;

    d) amplifying means, coupled to the at least one inductor means; and

    e) current source means coupled in serial to the amplifier;

    and wherein the digital control word applied to the plurality of multiple capacitance level capacitors is dynamically varied until the output frequency of the VCO is approximately equal to the desired output frequency.

    16. A method of automatically calibrating a voltage controlled oscillator (VCO) in an integrated circuit device, wherein the VCO produces an output frequency signal and wherein the VCO includes at least one tuning varactor coupled in parallel to at least one inductor, and wherein the capacitance of the tuning varactor is controlled by an analog tuning voltage V_{tune}, and wherein the at least one inductor is coupled in parallel to a plurality of multiple capacitance level capacitors, each multiple capacitance level capacitor having a plurality of steady-state capacitance levels, and wherein each multiple capacitance level capacitor is coupled to an associated and corresponding control signal, and wherein the capacitance level measured across the plurality of capacitors varies as a function of the corresponding control signal, and wherein the control signals together comprise a control word, the method comprising the steps of:

    a) applying a selected initial control word to the plurality of multiple capacitance level capacitors;

    b) waiting for a first pre-determined settling period to allow the VCO output signal time to settle, and then proceeding to step (c);

    c) comparing the analog tuning voltage V_{tune} to a predetermined low output threshold value $V_{out}L$, and proceeding to step (d) if V_{tune} is less than $V_{out}L$, else proceeding to step (h);

    d) waiting for a second pre-determined settling period to allow the VCO output signal time to settle, and then proceeding to step (e);

    e) comparing the analog tuning voltage V_{tune} to a predetermined high output threshold value $V_{out}H$, and returning to step (c) if V_{tune} is greater than $V_{out}H$, else proceeding to step (f);

    f) comparing the analog tuning voltage V_{tune} to the predetermined low output threshold value $V_{out}L$, and proceeding to step (g) if V_{tune} is less than $V_{out}L$, else returning to step (c);

    g) varying the control word applied to the plurality of multiple capacitance level capacitors by increasing the control word by one least significant bit (LSB) value, and then returning to step (c);

    h) comparing the analog tuning voltage V_{tune} to the predetermined high output threshold value $V_{out}H$, and proceeding to step (i) if V_{tune} is greater than $V_{out}H$, else returning to step (c);

i) waiting for the second predetermined settling period to allow the VCO output signal time to settle, and then proceeding to step (j);

j) comparing the analog tuning voltage V_{tune} to the predetermined low output threshold value $V_{out}L$, and returning to step (c) if V_{tune} is less than $V_{out}L$, else proceeding to step (k);

k) comparing the analog tuning voltage V_{tune} to the predetermined high output threshold value $V_{out}H$, and proceeding to step (1) if V_{tune} is greater than $V_{out}H$, else returning to step (c); and

l) varying the control word applied to the plurality of multiple capacitance level capacitors by decreasing the control word by one least significant bit (LSB) value, and returning to step (c).

17. The method of automatically calibrating a VCO as set forth in claim 16, wherein the steps are executed in software instructions by a microprocessor that is operatively coupled to the VCO.

18. The method of automatically calibrating a VCO as set forth in claim 16, wherein the initial control word applied in step (a) is approximately equal to one-half of a maximum attainable value of the control word.

19. The method of automatically calibrating a VCO as set forth in claim 16, wherein the second pre-determined settling period is approximately equal to 100 microseconds.

20. The method of automatically calibrating a VCO as set forth in claim 16, wherein the method does not proceed beyond step (b) if the VCO is being used in a radio system and wherein the radio system is currently receiving or transmitting voice or data information.

21. The method of automatically calibrating a VCO as set forth in claim 16, wherein the VCO is used in a frequency hop transceiver capable of generating receive and transmit frequencies in a wireless Time-Division Duplex scheme.

22. The method of automatically calibrating a VCO as set forth in claim 21, the method further comprising the steps of:

a) after the step (b) of waiting for a first pre-determined settling period, proceeding to sub-step (i):

i) determining whether the VCO is currently operating during a receive or transmit time slot;

ii) if the VCO is currently operating during a receive or transmit time slot, returning to sub-step (i), else proceeding to sub-step (iii);

iii) determining whether a channel jump or channel hop condition exists, and if no channel jump condition exists, proceeding to step (c) of claim 16, else proceeding to sub-step (iv);

iv) determining a difference in VCO center frequency required by the channel hop condition determined in sub-step (iii); and

v) updating the control word responsive to the difference determined during sub-step (iv).

23. The method of automatically calibrating a VCO as set forth in claim 22, wherein the control word that is applied to the plurality of multiple capacitance level capacitors represents a number of channels that is jumped during the channel jump condition determined during sub-step (iii).

24. The method of automatically calibrating a VCO as set forth in claim 22, wherein the control word is updated during sub-step (v) if and only if a channel jump exceeding a predetermined channel jump threshold is determined during sub-step (iii).

*   *   *   *   *