

SYSTEM AND METHOD FOR TUNING A VLSI CIRCUIT

BACKGROUND OF THE INVENTION

[0001] Field of the Invention

[0002] The present invention relates to electronic circuits and systems. More specifically, the present invention relates to electronic circuits and systems for generating accurate currents and voltages in integrated circuits.

[0003] Description of the Related Art

[0004] Accurate voltage, current and other references are needed in modern analog integrated circuit design. Currently, voltage is the only parameter that can be accurately generated on an integrated circuit chip. Other parameters, such as current, resistance, and capacitance, cannot currently be controlled more accurately than $\pm 15\text{--}40\%$ unless a special process of trimming is used. For this reason, circuits are typically designed to exploit ratios of currents, capacitors and/or resistances. If an absolute value is required (other than for voltage), it will usually have to be supplied through external pins on the circuit board. Unfortunately, this is not cost effective and increases the complexity of the circuit.

[0005] Accurate transconductance is often required in analog circuits. Transconductance (g_m) is the ratio of the output current to the input voltage. Currently, a constant g_m bias circuit can be used to generate an accurate transconductance (with an accuracy of $\pm 1\%$ or better), through the use of a single external resistor. The circuit uses an added pin and makes the application board more complicated. However, this is typically perceived to be a small price to pay for accurate control of g_m . After the transconductance of one transistor is defined, it is possible to control the transconductance of all transistors by the use of transistor and current ratios, which can

be accurately controlled in VLSI. Consequently, most analog circuits include a constant g_m bias circuit.

[0006] Some analog circuits also require an accurate current source, in addition to accurate transconductance, for such applications such as sensing, measurement, power control, and high frequency-low voltage. Currently, there is no way to generate an accurate current source without adding additional external devices, which add cost and complexity.

[0007] Furthermore, some circuits also require other accurate parameters, such as resistance or capacitance. Currently, there is no known way to accurately generate any parameters, other than voltage, without adding additional external devices, trimming or special processes.

[0008] Hence, a need remains in the art for an improved analog integrated circuit design offering multiple accurate reference sources in a cost-effective manner.

SUMMARY OF THE INVENTION

[0009] The need in the art is addressed by the present invention, which in a most general description provides a first circuit for generating a first accurate reference signal and a second circuit for generating a second accurate reference signal. The first and second circuits are disposed on a common substrate. A third mechanism is provided for alternately periodically coupling the first or second circuits to an external (off-substrate) device for providing an accurate reference signal.

[0010] In a specific embodiment, the invention provides a circuit for accurately tuning the absolute values of multiple parameters, such as current, transconductance, resistance, and/or capacitance, in a VLSI system with minimal changes to existing transconductance bias circuits by reusing an single external resistor.

[0011] In an illustrative embodiment, the invention includes a first circuit for generating an accurate transconductance using a single external resistor R_{ext} ; a second

circuit for generating an accurate current reference using the same external resistor R_{ext} ; and a third circuit for alternately switching on and off the first and second circuits in order to share the external resistor R_{ext} .

[0012] In the illustrative embodiment, the first circuit includes four transistors $M1_G$, $M2$, $M3_G$, and $M4_G$ and an external resistor R_{ext} connected as a constant transconductance bias circuit. The gate of $M3_G$ is connected to the gate of $M4_G$ by a switch S_{G4} , the gate of $M1_G$ is connected to the gate of $M2$ by a switch S_{G2} , and the source of $M3_G$ is connected to the source of $M4_G$ by two switches S_{G1} and S_{G3} . These switches are turned on when tuning the transconductance, and turned off otherwise. The gate of $M4_G$ is connected to a capacitor $C2$, which is used to hold the bias voltage of the transconductance circuit while the circuit is allocated to another task.

[0013] The second circuit includes four transistors $M1_I$, $M2$, $M3_I$, and $M4_I$ and the external resistor R_{ext} connected as a constant transconductance bias circuit, with one modification: the source of $M1_I$ is connected to a voltage source V_{ref} . This voltage source can be supplied accurately on chip by a bandgap voltage reference. This circuit generates a current given by $I = V_{ref}/R_{ext}$. Since both quantities V_{ref} and R_{ext} are defined accurately, the current will also be known accurately. Switches are connected in a similar fashion as in the first circuit. These switches are turned on when tuning the current, and turned off otherwise. The gate of $M4_I$ is connected to a capacitor $C1$ which is used to hold the bias voltage of the current circuit while the circuit is allocated to another task.

[0014] In a specific embodiment, the third circuit includes several switches controlled by a digital counter for turning off portions of the circuit which are not in use. In the illustrative embodiment, the invention further includes a fourth circuit for generating an additional accurate reference parameter. The fourth circuit can generate an accurate internal resistance R_{int} , an accurate r_{DS} , and/or an accurate internal capacitance C_{int} .

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Fig. 1 is a simplified schematic diagram of a typical constant transconductance g_m bias circuit of conventional design and construction.

[0016] Fig. 2 is a simplified schematic diagram of a g_m bias circuit modified to generate an accurate current reference in accordance with the teachings of the present invention.

[0017] Fig. 3 is a simplified schematic diagram of a g_m bias circuit modified to generate an accurate drain to source resistance r_{DS} in a transistor M0 in accordance with the teachings of the present invention.

[0018] Fig. 4 is a simplified schematic diagram of a g_m bias circuit modified to generate an accurate internal resistance R_{int} in accordance with the teachings of the present invention.

[0019] Fig. 5 is a simplified schematic diagram of a g_m bias circuit modified to generate an accurate internal capacitance C_{int} in accordance with the teachings of the present invention.

[0020] Fig. 6 is a simplified schematic diagram of a g_m bias circuit modified to generate accurate transconductance, current, and internal resistance all at the same time by reusing the external resistor in accordance with the teachings of the present invention.

DESCRIPTION OF THE INVENTION

[0021] Illustrative embodiments and exemplary applications will now be described with reference to the accompanying drawings to disclose the advantageous teachings of the present invention.

[0022] While the present invention is described herein with reference to illustrative embodiments for particular applications, it should be understood that the invention is not limited thereto. Those having ordinary skill in the art and access to

the teachings provided herein will recognize additional modifications, applications, and embodiments within the scope thereof and additional fields in which the present invention would be of significant utility.

[0023] Currently, most analog circuits need an accurate transconductance g_m reference. A constant g_m bias circuit 10 such as that shown in Fig. 1 is typically used to fulfill this need.

[0024] Fig. 1 is a simplified schematic diagram of a typical constant transconductance g_m bias circuit of conventional design and construction. This circuit uses an external resistor R_{ext} , which can have an accuracy of $\pm 1\%$ or better, to set up a current through a transistor M2 such that the transconductance of the transistor has an accuracy similar to that of the external resistor.

[0025] The g_m bias circuit is comprised of four transistors M1, M2, M3, and M4 connected to the external resistor R_{ext} . The transistors M1 and M4 are connected as diodes. The drain of M1 connected to the drain of M3, the drain of M2 connected to the drain of M4, the source of M3 and the source of M4 connected to a voltage source Vdd, the source of M2 connected to one terminal of the external resistor R_{ext} , and the source of M1 and the other terminal of R_{ext} connected to ground. The transistor M2 is four times larger than M1. The transistors M3 and M4 are identical and connected as a current mirror, ensuring that $I_1 = I_2$. Assuming that these two transistors are in saturation yields:

$$V_{eff1} = \sqrt{4} V_{eff2} \quad [1]$$

$$V_{GS1} - V_T = 2(V_{GS2} - V_T) \quad [2]$$

$$V_{GS1} = 2V_{GS2} - V_T \quad [3]$$

where V_{GSi} is the gate to source voltage of M_i , $V_{effi} = V_{GSi} - V_T$, and V_T is the threshold voltage of the transistors. Analyzing the loop consisting of M1, M2, and R_{ext} and substituting for V_{GS1} results in the following equations:

$$V_{GS1} = V_{GS2} + I_2 R_{ext} \quad [4]$$

$$2V_{GS2} - V_T = V_{GS2} + I_2 R_{ext} \quad [5]$$

$$V_{GS2} - V_T = I_2 R_{ext} \quad [6]$$

$$V_{eff2} = I_2 R_{ext} \quad [7]$$

$$g_m = I_2 / V_{eff2} = 1 / R_{ext} \quad [8]$$

Thus, the transconductance g_m of M2 is dependent only on R_{ext} , and will have a tolerance equivalent to that of R_{ext} ($\pm 1\%$). Once the transconductance of one transistor is defined, it is possible to control the transconductance of all transistors by the use of transistor and current ratios, which can be accurately controlled in VLSI.

[0026] Several applications, such as sensing, measurement, power control, and high frequency-low voltage, require an accurate current reference.

[0027] Fig. 2 is a simplified schematic diagram of a circuit 20 for generating an accurate current reference by a simple modification of the g_m bias circuit of Fig. 1 in accordance with the teachings of the present invention.

[0028] This circuit 20 is identical to the g_m bias circuit 10 of Fig. 1 with a few modifications: the transistors M1 and M2 are now identical; and the source of M2 is fixed at a reference voltage V_{ref} , which can be generated accurately on chip by a bandgap voltage source. Since the same gate voltage is applied to M1 and M2, and M1 and M2 have the same geometries, the source voltage of M2 is forced to also be V_{ref} . The current I_R through the external resistor R_{ext} is therefore well defined (since both V_{ref} and R_{ext} are accurate):

$$I_R = I_2 = V_{ref} / R_{ext}, \quad [9]$$

and therefore the current through M3 is also well defined (since $I_1 = I_2$). This current I_1 can then be mirrored to serve as a current reference.

[0029] Fig. 3 is a simplified schematic diagram of a modified g_m bias circuit 30 used to generate an accurate drain to source resistance r_{DS} in a transistor M_0 in accordance with the teachings of the present invention. An accurate r_{DS} is useful in

many applications, such as sensors or for controlling the common-mode of a $g_m C$ filter.

[0030] This circuit 30 is identical to the accurate current source circuit 20 of Fig. 2 with a few modifications: an additional transistor M0 replaces the voltage source V_{ref} at the source of M1; and an op-amp K senses the voltages at the source of M1 and the source of M2, and adjusts the gate of M0 accordingly, so that the source voltages of M1 and M2 will be equal. The r_{DS} of M0 is thus forced to be equal to R_{ext} :

$$r_{DS} = R_{ext} \quad [10]$$

A capacitor C_r is also connected to the gate of M0 for stability.

[0031] In practice, the resistors inside a chip may be expected to have an accuracy of $\pm 20\%$, or worse.

[0032] Fig. 4 is a simplified schematic diagram of a modified g_m bias circuit 40 used to generate an accurate internal resistance R_{int} in accordance with the teachings of the present invention. This circuit matches an internal resistance R_{int} to the external resistor R_{ext} , which typically has a tolerance of $\pm 1\%$. An accurate resistance is useful in applications such as A/D converters.

[0033] This circuit 40 is identical to the accurate current source circuit 20 of Fig. 2 with a few modifications. For example, the source of M1, instead of the voltage source V_{ref} , is connected to an array of binary weighted resistors ($2^0 R$, $2^1 R \dots 2^N R$), in series with a resistor R2 which is chosen to be equal to $R_{ext} - 20\%$, so that R2 is certain to be less than R_{ext} . This forms the internal resistance R_{int} . The resistors in the array are connected to switches ($S_0, S_1 \dots S_N$), which are controlled by a successive approximation register (SAR). A comparator (CMP) compares the internal resistance R_{int} with R_{ext} , and tells the SAR whether to increase or decrease the internal resistance. The SAR successively switches the resistors in the array on and off until the total internal resistance matches R_{ext} :

$$R_{int} = R_{ext} \quad [11]$$

This resistance can then be copied elsewhere in the circuit by simply taking the sequence for the switches ($O = O_0O_1...O_N$) from the SAR and applying it to similar arrays of resistors.

[0034] Fig. 5 is a simplified schematic diagram of a modified g_m bias circuit 50 used to generate an accurate internal capacitance C_{int} in accordance with the teachings of the present invention. This is useful for low power consumption circuits. This circuit includes the circuit 20 of Fig. 2, plus two additional transistors M5 and M6. The gate of transistor M5 is connected to the gate of transistor M1 (in circuit 20), and the gate of transistor M6 is connected to the gate of transistor M2 (in circuit 20). The drains of transistors M5 and M6 are connected to each other. The source of transistor M6 is connected to Vdd. The source of transistor M5 is connected to an array of binary weighted capacitors ($2^0C, 2^1C...2^NC$) each connected in parallel with a capacitor C0. These capacitors form the internal capacitance C_{int} . A switch S controlled by a clock Φ is connected in parallel to the capacitor array. The capacitors in the array are connected to switches ($S_0, S_1...S_N$), which are controlled by a successive approximation register (SAR). The SAR is controlled by the clock Φ . A comparator (CMP) compares the voltage on the capacitor array with the reference voltage V_{ref} (in circuit 20), and tells the SAR whether to increase or decrease the internal capacitance. This capacitance can then be copied elsewhere in the circuit by simply taking the sequence for the switches ($O = O_0O_1...O_N$) from the SAR and applying it to similar arrays of capacitors.

[0035] In the circuit 50 of Fig. 5, the circuit 20 is used to generate a constant current which is dumped on the capacitor array for a given interval defined by the duration of the low time of the reset clock Φ_{bar} (with a well defined duration ΔT which derives from an accurate crystal oscillator). The final value of the voltage on the capacitor is compared to a reference voltage while the successive approximation algorithm is used to tune the capacitor to the desired value:

$$C_{int} = \Delta T * I_{ref} / V_{ref} \quad [12]$$

where I_{ref} is the current at V_{ref} .

[0036] More circuits can be generated in a similar fashion to control other parameters.

[0037] Finally, several circuits can be combined to control multiple parameters at once by reusing the external resistor. Since an external device requires a pin and results in a more complicated circuit board layout, it would be highly desirable not to use more pins for tuning internal components. This can be achieved easily by the use of some switches.

[0038] Fig. 6 is a simplified schematic diagram of a circuit 100 which generates accurate transconductance, current, and internal resistance all at the same time by reusing the external resistor in accordance with the teachings of the present invention. In the preferred embodiment, the circuit is disposed on a common substrate, except for the single external device, the resistor.

[0039] This circuit combines the circuits of Fig. 1, Fig. 2, and Fig. 4 with a switching circuit 60 that periodically switches to the desired reference generating circuit, turning off the portions of the circuit which are not in use. The switching circuit 60 includes several switches: S_{G1} , S_{G2} , S_{G3} , S_{G4} , S_{I1} , S_{I2} , S_{I3} , S_{I4} , S_{R1} , S_{R2} , and S_{R3} . A digital counter allocates the portion of the circuit that generates the constant g_m , I , or R_{int} to the external resistor R_{ext} . The resultant bias voltages for the g_m and I circuits are refreshed periodically on capacitors $C1$ and $C2$, respectively. These capacitors hold the desired bias voltage when the reference generating circuit is allocated to another task (such as fixing the R , I , or g_m). Outputs O_I and O_G provide the accurate current reference and the accurate transconductance reference current which is continuously available to other blocks of the same substrate.

[0040] Circuits 14 and 16 combine with the transistor $M2$ and the external resistor R_{ext} to form an accurate transconductance circuit similar to that of Fig. 1 (circuit 10). This occurs when switches S_{G1} , S_{G2} , S_{G3} , and S_{G4} are on, and all other switches are off.

[0041] Circuit 14 is comprised of a transistor $M1_G$ connected as a diode, and a transistor $M3_G$. The drain of $M1_G$ is connected to the drain of $M3_G$. The source of $M1_G$ is connected to ground. A switch S_{G1} connects the source of $M3_G$ to Vdd. A switch S_{G2} connects the gate of $M1_G$ to the gate of M2. Circuit 16 is comprised of a transistor $M4_G$ and a capacitor C2 connected between Vdd and the gate of $M4_G$. A switch S_{G3} connects the source of $M4_G$ to Vdd. A switch S_{G4} connects the gate of $M4_G$ to the gate of $M3_G$ in circuit 14.

[0042] Circuits 24 and 26 combine with the transistor M2 and the external resistor R_{ext} to form an accurate current circuit similar to that of Fig. 2 (circuit 20). This occurs when switches S_{I1} , S_{I2} , S_{I3} , and S_{I4} are on, and all other switches are off.

[0043] Circuit 24 is comprised of a transistor $M1_I$ connected as a diode, and a transistor $M3_I$. The drain of $M1_I$ is connected to the drain of $M3_I$. The source of $M1_I$ is connected to a voltage source V_{ref} . A switch S_{I1} connects the source of $M3_I$ to Vdd. A switch S_{I2} connects the gate of $M1_I$ to the gate of M2. Circuit 26 is comprised of a transistor $M4_I$ and a capacitor C1 connected between Vdd and the gate of $M4_I$. A switch S_{I3} connects the source of $M4_I$ to Vdd. A switch S_{I4} connects the gate of $M4_I$ to the gate of $M3_I$ in circuit 24.

[0044] Circuits 42, 44, and 46 combine with the transistor M2 and the external resistor R_{ext} to form an accurate internal resistance circuit similar to that of Fig. 4 (circuit 40). This occurs when switches S_{R1} , S_{R2} , and S_{R3} are on, and all other switches are off.

[0045] Circuit 42 is comprised an array of binary weighted resistors (2^0R , $2^1R \dots 2^NR$). The resistors in the array are connected to ground by switches (S_0 , $S_1 \dots S_N$), which are controlled by a successive approximation register (SAR). A comparator (CMP) compares the internal resistance R_{int} generated by the array of resistors with R_{ext} and outputs the result to the SAR. Circuit 44 is comprised of a transistor $M1_R$ connected as a diode, and a transistor $M3_R$. The drain of $M1_R$ is connected to the drain of $M3_R$. The source of $M1_R$ is connected to the array of resistors in circuit 42. A switch S_{R1} connects the source of $M3_R$ to Vdd. A switch S_{R2} connects the gate of $M1_R$ to the gate of M2. Circuit 46 is comprised of a

transistor M4_R. A switch S_{R3} connects the source of M4_R to Vdd. The drain of M4_R is connected to the drain of M2.

[0046] Thus, the present invention reuses the external resistor R_{ext} to generate alternative biasing or tuning tasks. With very minor changes (a single transistor, a capacitor, and some switches), the inventive g_m bias circuit can be used to generate an accurate current (e.g., with tolerance of $\pm 1\%$). The g_m bias circuit can also use the accurate external resistance to periodically tune the r_{DS} of a transistor, internal resistance R_{int}, and/or capacitance C_{int}, (e.g., to an accuracy of $\pm 1\%$, in comparison with typical current tolerances of $\pm 15\%$ to $\pm 40\%$).

[0047] The present invention has been described herein with reference to a particular embodiment for a particular application. Those having ordinary skill in the art and access to the present teachings will recognize additional modifications, applications and embodiments within the scope thereof. For example, the present teachings are not limited to VLSI technology and can be used in any integrated circuit application such as LSI. Further, the external device is not limited to a resistor. The present invention may be implemented using any external reference, such as current, without departing from the scope of the present teachings.

[0048] It is therefore intended by the appended claims to cover any and all such applications, modifications and embodiments within the scope of the present invention.

CLAIMS

1. A circuit (100), adaptively coupled to a common external resource, for generating multiple accurate reference signals characterized by:

a first circuit (10) for generating a first refreshable accurate reference signal;

a second circuit (20) for generating a second refreshable accurate reference signal; and

a switching circuit (60) coupled to each of the first and second circuits to selectively refresh the associated reference signals.

2. The biasing circuit of Claim 1 wherein the switching circuit (60) includes switches which in the on position operate to refresh the associated generated reference signal.

3. The biasing circuit of Claim 1 wherein the circuit (100) further includes a third circuit for generating one or more additional accurate reference signals while using the same external device.

4. The biasing circuit of Claim 1 wherein the external resource is a resistor R_{ext} .

5. The biasing circuit of Claim 1 wherein the first, second, and switching circuits are disposed on a common substrate.

6. The biasing circuit of Claim 4 wherein the first accurate reference signal is transconductance, and the first circuit (10) includes four transistors $M1_G$, $M2$, $M3_G$, and $M4_G$ connected as a constant transconductance bias circuit with:

$M1_G$ and $M4_G$ connected as diodes;

the drain of $M1_G$ connected to the drain of $M3_G$;

the drain of $M2$ connected to the drain of $M4_G$;

the source of $M2$ connected to one terminal of the external resistor R_{ext} ; and,

the source of $M1_G$ and the other terminal of R_{ext} connected to ground.

7. The biasing circuit of Claim 6 wherein the gate of $M3_G$ is connected to the gate and drain of $M4_G$ by a switch S_{G4} , the gate of $M1_G$ is connected to the gate of $M2$ by a switch S_{G2} , and the source of $M3_G$ is connected to the source of $M4_G$ by two switches S_{G1} and S_{G3} .

8. The biasing circuit of Claim 6 wherein the gate of $M4_G$ is connected to a capacitor $C2$.

9. The biasing circuit of Claim 4 wherein the second accurate reference signal is current, and the second circuit (20) includes four transistors $M1_I$, $M2$, $M3_I$, and $M4_I$ connected as a constant current bias circuit with:

$M1_I$ and $M4_I$ connected as diodes;

the drain of $M1_I$ connected to the drain of $M3_I$;

the drain of $M2$ connected to the drain of $M4_I$;

the source of $M2$ connected to the external resistor R_{ext} ; and,

the source of $M1_I$ connected to a voltage source V_{ref} .

10. The biasing circuit of Claim 9 wherein the gate of $M3_I$ is connected to the gate and drain of $M4_I$ by a switch S_{I4} , the gate of $M1_I$ is connected to

the gate of M2 by a switch S_{I2} , and the source of M3_I is connected to the source of M4_I by two switches S_{I1} and S_{I3} .

11. The biasing circuit of Claim 3 wherein the third circuit includes an accurate internal resistance R_{int} bias circuit (40), an accurate drain to source resistance r_{DS} bias circuit (30), and/or an accurate internal capacitance C_{int} bias circuit (50).