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Cascode Amplifier Bias Circuits

Abstract

Bias circuits and methods for silicon-based amplifier architectures that are tolerant of supply and bias voltage variations, bias current variations, and transistor stack height, and compensate for poor output resistance characteristics. Embodiments include power amplifiers and low-noise amplifiers that utilize a cascode reference circuit to bias the final stages of a cascode amplifier under the control of a closed loop bias control circuit. The closed loop bias control circuit ensures that the current in the cascode reference circuit is approximately equal to a selected multiple of a known current value by adjusting the gate bias voltage to the final stage of the cascode amplifier. The final current through the cascode amplifier is a multiple of the current in the cascode reference circuit, based on a device scaling factor representing the relative sizes of the transistor devices in the cascode amplifier and in the cascode reference circuit.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS—CLAIM OF PRIORITY [0001] The present application is a continuation of, and claims priority to, commonly assigned U.S. patent application Ser. No. 18/624,973, filed Apr. 2, 2024, entitled “Cascode Amplifier Bias Circuits”, and the contents of said Ser. No. 18/624,973 application is incorporated herein by reference in its entirety. Application Ser. No. 18/624,973 is a continuation of, and claims priority to, commonly assigned U.S. patent application Ser. No. 18/322, 166, filed May 23, 2023, entitled “Cascode Amplifier Bias Circuits”, to issue on Apr. 9, 2024 as U.S. Pat. No. 11,955,932, and the contents of said Ser. No. 18/322, 166 application is incorporated herein by reference in its entirety. application Ser. No. 18/322,166 is a continuation of, and claims priority to, commonly assigned U.S. patent application Ser. No. 17/843,372, filed Jun. 17, 2022, entitled “Cascode Amplifier Bias Circuits”, issued on May 30, 2023 as U.S. Pat. No. 11,664,769, and the contents of said Ser. No. 17/843,372 application is incorporated herein by reference in its entirety. application Ser. No. 17/843,372 is a divisional of, and claims priority to, commonly assigned U.S. patent application Ser. No. 16/935,999, filed Jul. 22, 2020, entitled “Cascode Amplifier Bias Circuits”, issued on Jun. 28, 2022 as U.S. Pat. No. 11,374,540, and the contents of said Ser. No. 16/935,999 application is incorporated herein by reference in its entirety. Application Ser. No. 16,935,999 is a divisional of, and claims priority to, commonly assigned U.S. patent application Ser. No. 16/250,889, filed Jan. 17, 2019, entitled “Cascode Amplifier Bias Circuits”, now U.S. Pat. No. 10,756,678, issued Aug. 25, 2020, and the contents of said Ser. No. 16/250,889 application is incorporated herein by reference in its entirety. Application Ser. No. 16/250,889 is a divisional of, and claims priority to, commonly assigned U.S. patent application Ser. No. 15/268,229, filed Sep. 16, 2016, entitled “Cascode Amplifier Bias Circuits”, now U.S. Pat. No. 10,250,199, issued Apr. 2, 2019, and the contents of said Ser. No. 15/268,229 application is incorporated herein by reference in its entirety. [0002] The present application is related to U.S. application Ser. No. 15/268,297 entitled “Standby Voltage Condition for Fast RF Amplifier Bias Recovery” (Attorney Docket No. PER-195-PAP)

filed on Sep. 16, 2016 (now U.S. Pat. No. 9,837,965 issued Dec. 5, 2017), the disclosure of which is incorporated herein by reference in its entirety. The present application is also related to U.S. application Ser. No. 15/268,275 entitled "Gate Drivers for Stacked Transistor Amplifiers" (Attorney Docket No. PER-194-PAP) filed on Sep. 16, 2016 (now U.S. Pat. No. 9,843,293 issued Dec. 12, 2017), the disclosure of which is incorporated herein by reference in its entirety. The present application is also related to U.S. application Ser. No. 15/268,257 entitled "Body Tie Optimization for Stacked Transistor Amplifier" (Attorney Docket No. PER-199-PAP) filed on Sep. 16, 2016 (now U.S. Pat. No. 9,882,531 issued Jan. 30, 2018), the disclosure of which is incorporated herein by reference in its entirety. [0003] The present application may be related to U.S. Pat. No. 7,248,120, issued on Jul. 24, 2007, entitled "Stacked Transistor Method and Apparatus", the disclosure of which is incorporated herein by reference in its entirety. The present application may be related to Published US Application No. 2015/0270806 A1, published Sep. 24, 2015, entitled "Bias Control for Stacked Transistor Configuration", the disclosure of which is incorporated herein by reference in its entirety. The present application may also be related to Published US Application No. 2014/0184335 A1, published Jul. 3, 2014, entitled "Amplifiers Operating in Envelope Tracking Mode or Non-Envelope Tracking Mode" (Attorney Docket No. PER-087-PAP), the disclosure of which is incorporated herein by reference in its entirety. The present application may also be related to Published US Application No. US 2014/0184336 A1, published Jul. 3, 2014, entitled "Amplifier Dynamic Bias Adjustment for Envelope Tracking", the disclosure of which is incorporated herein in its entirety. The present application may also be related to U.S. Pat. No. 9,219,445 entitled "Optimization Methods for Amplifier with Variable Supply Power", issued Dec. 22, 2015, the disclosure of which is incorporated herein by reference in its entirety. The present application may also be related to U.S. Pat. No. 8,487,706 B2 entitled "Stacked Linear Power Amplifier with Capacitor Feedback and Resistor Isolation", issued Jul. 16, 2013, the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

(1) Technical Field

[0004] The invention relates to electronic circuits, and more particularly to bias circuits for cascode amplifiers, particularly radio frequency cascode amplifiers.

(2) Background

[0005] Amplifiers are a common component in radio frequency (RF) transmitters and receivers, and are frequently used for power amplification of transmitted RF signals and for low-noise amplification of received RF signals. For many RF systems, particularly those requiring portability (e.g., cellular telephones, WiFi-connected computers, cameras, and other devices, etc.), it has become common to use complementary metal-oxide semiconductor (CMOS) fabrication technology to create low cost, low power, complex integrated circuits (ICs). CMOS device technology improvements, such as silicon-on-sapphire (SOS) CMOS, silicon-on-insulator (SOI) CMOS, and ever-shrinking field-effect transistor (FET) device channel lengths, are putting the RF performance metrics of silicon-based CMOS transistors on par with rival gallium arsenide (GaAs) technologies.

[0006] FIG. 1 is a simplified schematic diagram of a prior art amplifier circuit **100**. The illustrated circuit **100** has a cascode common source architecture constructed from two series-connected FETs. An RF input signal, RFIN, is applied through a biasing and coupling circuit **102** to the gate of a FET **M1**, the drain of which is coupled to (and thus drives) the source of a second FET **M2**. The source of **M1** is coupled thorough a degeneration inductor **L** to RF ground. The degeneration inductor **L**, which will also have an inherent resistance **R** (shown in dotted outline), performs several functions, including obtaining a good dynamic range (e.g., a good noise figure), achieving high sensitivity with low power consumption, helping make input impedance matching easier, and improving linearity.

[0007] The second FET M2 has its gate coupled to a voltage source V_{gate} (which may be $V_{sub,DD}$ in many cases) and provides an amplified RF output signal, RFOUT, at its drain. In some applications, the RF input signal, RFIN, may be processed through an input impedance matching network **104** before being coupled to the gate of M1, and in some applications, the RF output signal, RFOUT, may be processed through an output impedance matching network **106**. While the illustrated cascode circuit provides good isolation because there is no direct coupling from the output to the input, the circuit is not well suited to applications in which the DC supply voltage varies, such as applications where the DC supply voltage at the drain is actively modified to optimize operation at different power levels; examples are average power tracking (APT), envelope tracking (ET), and GSM power amplifier power control. In these examples, the supply voltage $V_{sub,DD}$ may have a range that varies by a factor of 10 or more (e.g., from 4.5V to 0.4V, as one example).

[0008] One problem area for using silicon-based CMOS transistors in cascode amplifier circuits is creating bias circuits, particularly in cases in which the DC supply voltage varies and in the case of amplifiers with a transistor stack height of 3 or more. In general, a DC bias voltage applied to the gate of a FET sets the gate-source voltage V_s so as to provide a desired drain current. Silicon-based CMOS devices with short channel lengths provide fast RF response—a desirable characteristic in an amplifier—but suffer from poor output resistance characteristics due to the influence of the drain voltage on the gate of a transistor device. As such, they are not amenable to common open-loop bias techniques, such as current mirrors, without suffering from a large and undesirable mismatch between a reference device current and the output device current. In addition, the problem can be further exasperated in SOS and SOI CMOS technologies due to issues associated with the floating body or “kink” effect. In the floating body effect, the body of a transistor may form a capacitor with the insulated substrate; charge accumulation on this capacitor may cause the formation of parasitic transistors consuming unwanted parasitic currents and further degrading the output resistance of devices intended to be used as current sources.

[0009] Another challenge in designing bias circuits for silicon-based CMOS cascode amplifiers is to configure such circuits so that they are tolerant of supply and bias voltage variations, and bias current variations. Traditional cascode bias circuits include diode connected devices which do not accommodate a wide range of supply and bias voltages. Bias current variations may be driven by variations in process, temperature, and voltage (i.e., “PVT” effects), the end result of which is to cause fluctuations in bias current leading to fluctuations in RF performance. Another drawback to using silicon-based CMOS devices for amplifier applications, and particularly for power amplifier applications, is a relatively low breakdown voltage per device.

[0010] Yet another challenge in designing RF amplifiers is that, in many applications, the RF electrical environment of a transmitter, receiver, or transceiver is constantly changing. The changing characteristics of an RF signal path affects RF circuit performance metrics such as gain, linearity, noise figure, and power consumption. A system performance profile that ideally sets such metrics for one situation (such as high gain, moderate linearity, and low noise in the presence of a small received signal) can be completely inappropriate as the RF environment changes (such as with increasing received signal power). These situation transitions can occur many times during a single usage session of an RF circuit (for example, as a cellular phone moves relative to signal towers), and not adjusting to an appropriate performance profile as the RF environment changes can result in poor or non-functioning RF circuit performance.

[0011] Accordingly, there is a need for bias circuits for silicon-based CMOS amplifier architectures that are tolerant of supply and bias voltage variations, bias current variations, and transistor stack height, and compensate for the poor output resistance characteristics of silicon-based CMOS devices with short channel lengths. There is also a need for amplifier architectures that can rapidly adapt to a changing RF electrical environment. Further, there is a need for improved silicon-based CMOS amplifier architectures having good isolation.

SUMMARY OF THE INVENTION

[0012] The invention encompasses bias circuits and methods for silicon-based CMOS amplifier architectures that are tolerant of supply and bias voltage variations, bias current variations, and transistor stack height, and compensate for the poor output resistance characteristics of silicon-based CMOS devices with short channel lengths. Further, the invention encompasses improved silicon-based CMOS amplifier architectures that can rapidly adapt to a changing RF electrical environment, and which have good isolation. The disclosed amplifier architectures are adaptable to a number of amplifier applications, including power amplifiers (PAs) and low-noise amplifiers (LNAs).

[0013] Embodiments of the invention utilize a cascode reference circuit to bias the final stages of a cascode amplifier under the control of a closed loop bias control circuit. The closed loop bias control circuit ensures that the current in the cascode reference circuit is approximately equal to a selected multiple of a known current value by adjusting the gate bias voltage to the final stage of the cascode amplifier. The final current through the cascode amplifier is a multiple of the current in the cascode reference circuit, based on a device scaling factor m representing the size of the transistor devices in the cascode amplifier versus the size of the transistor devices in the cascode reference circuit. A notable attribute of such an architecture is that the cascode reference circuit accommodates arbitrary variations in its supply voltage.

[0014] In some embodiments, the closed loop bias control circuit is digitally programmable such that the biased current through the cascode amplifier can be dynamically adjusted during operation. In some embodiments, in order to overcome the breakdown voltage liability of individual silicon-based CMOS devices, the cascode amplifier and/or the cascode reference circuit include a “stack” of two or more series-connected silicon-based CMOS devices so that the total RF voltage swing occurring across the stack is distributed over two or more CMOS devices; the stack height of the cascode amplifier and the cascode reference circuit need not be the same.

[0015] The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

Description

DESCRIPTION OF THE DRAWINGS

[0016] FIG. 1 is a simplified schematic diagram of a prior art amplifier circuit.

[0017] FIG. 2A is a simplified schematic diagram of a generalized embodiment of an amplifier circuit in accordance with the present invention.

[0018] FIG. 2B is a more detailed amplifier circuit showing some additional elements that may be added to the amplifier circuit of FIG. 2A.

[0019] FIG. 2C is a schematic diagram of one embodiment of an input impedance matching network that may be used in conjunction with the circuit of FIG. 2B.

[0020] FIG. 2D is a schematic diagram of one embodiment of an output impedance matching network that may be used in conjunction with the circuit of FIG. 2B.

[0021] FIG. 2E is a schematic diagram of one embodiment of a switchable resistance de-coupling network that may be used in conjunction with the circuit of FIG. 2B.

[0022] FIG. 3 is a simplified schematic diagram of an amplifier circuit having a cascode reference circuit configured with a first closed loop bias control circuit.

[0023] FIG. 4 is a simplified schematic diagram of an amplifier circuit having a cascode reference circuit configured with a second closed loop bias control circuit.

[0024] FIG. 5 is a simplified schematic diagram of an amplifier circuit having a cascode reference circuit configured with a third closed loop bias control circuit.

[0025] FIG. 6 is a simplified schematic diagram of an amplifier circuit having a cascode reference circuit configured with a fourth closed loop bias control circuit.

[0026] FIG. 7 is a simplified schematic diagram of an amplifier circuit having a cascode reference circuit configured with a fifth closed loop bias control circuit.

[0027] FIG. 8 is a simplified schematic diagram of an amplifier circuit having a cascode reference circuit configured with a sixth closed loop bias control circuit.

[0028] FIG. 9 is a flowchart showing one method for automatically biasing the final stages of a cascode amplifier.

[0029] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION OF THE INVENTION

[0030] The invention encompasses bias circuits and methods for silicon-based CMOS amplifier architectures that are tolerant of supply and bias voltage variations, bias current variations, and transistor stack height, and compensate for the poor output resistance characteristics of silicon-based CMOS devices with short channel lengths. Further, the invention encompasses improved silicon-based CMOS amplifier architectures that can rapidly adapt to a changing radio frequency (RF) electrical environment, and which have good isolation. The disclosed amplifier architectures that are adaptable to a number of amplifier applications, including power amplifiers (PAs) and low-noise amplifiers (LNAs).

[0031] Embodiments of the invention utilize a cascode reference circuit to bias the final stages of a cascode amplifier under the control of a closed loop bias control circuit. The closed loop bias control circuit ensures that the current in the cascode reference circuit is approximately equal to a selected multiple of a known current value by adjusting the gate bias voltage to the final stage of the cascode amplifier. The final current through the cascode amplifier is a multiple of the current in the cascode reference circuit, based on a device scaling factor m representing the size of the transistor devices in the cascode amplifier versus the size of the transistor devices in the cascode reference circuit. A notable attribute of such an architecture is that the cascode reference circuit accommodates arbitrary variations in its supply voltage.

[0032] In some embodiments, the closed loop bias control circuit is digitally programmable such that the biased current through the cascode amplifier can be dynamically adjusted during operation. In some embodiments, in order to overcome the breakdown voltage liability of individual silicon-based CMOS devices, the cascode amplifier and/or the cascode reference circuit includes a “stack” of two or more series-connected silicon-based CMOS devices so that the total RF voltage swing occurring across the stack is distributed over two or more CMOS devices; the stack height of the cascode amplifier and the cascode reference circuit need not be the same.

[0033] More particularly, some desirable design criteria for a cascode reference circuit used to bias the final stages of a cascode amplifier under the control of a closed loop bias control circuit include:

[0034] Controlling the quiescent current, I_{final} , in the cascode amplifier such that I_{final} is a known scaling factor of I_{mirror} (i.e., $I_{\text{final}} = m \cdot I_{\text{mirror}}$, where m is a constant scaling factor chosen in the design phase). This relation should hold over specified ranges for variations in process, voltage, and temperature. Any temperature profile (e.g., Zero Temperature Coefficient or ZTC, Proportional To Absolute Temperature or PTAT, Constant— $G_{\text{sub},M}$, etc.) in quiescent current that may be desirable for keeping the cascode amplifier within its specified limits for RF performance metrics may be implemented in the design of the I_{mirror} circuit.

[0035] In order to offset the poor output resistance of silicon-based CMOS devices with short channel lengths, an additional constraint is matching the corresponding drain voltages of the bottom (first) stage of the cascode amplifier and the cascode reference circuit. Theoretically, if the drain, source, and gate voltages of M_{b1} and M_1 match each other, then the current in the amplifier will accurately mirror the current in the reference circuit. Further, if the drain voltages and the gate voltages match between the bottom stage of the cascode reference circuit and the cascode amplifier,

then the output impedance problem is greatly mitigated or even eliminated. A feedback control loop can keep current constant independent of voltage, effectively providing a higher output resistance for a current source.

[0036] Adequate RF isolation/filtering from the RF signal input node to the common bias node of the cascode reference circuit such that the RF input signal does not perturb or corrupt the operation of the cascode reference circuit at DC or low frequencies. A general rule of thumb is to keep the RF voltage swing on the common bias node at or below about 10 mV zero-to-peak. In general, this criterion imposes an additional requirement on the cascode reference circuit—namely, it must be able to drive a sometimes sizable filter capacitance while maintaining adequate gain and phase margin for stable closed loop operation and acceptable transient response.

[0037] Adequate RF isolation/filtering between higher stage devices in the cascode amplifier and corresponding stages of the cascode reference circuit.

[0038] Minimizing current, since current spent generating bias voltages is seen as overhead current for the amplifier and counted against the DC power consumption set by the amplifier efficiency specifications.

[0039] Providing a baseband bandwidth for the control loop that is sufficiently high to allow for high data-rate standards (such as LTE, W-CDMA, etc. in cellular telephone systems). Insufficient baseband bandwidth in the cascode reference circuit may lead to degradation of power amplifier performance metrics, manifested as poor or asymmetric Adjacent Channel Power Ratio (ACPR) characteristics, poor Error Vector Magnitude (EVM) characteristics, and more.

General Biasing Architecture for Cascode Amplifier

[0040] FIG. 2A is a simplified schematic diagram of a generalized embodiment of an amplifier circuit **200** in accordance with the present invention. A cascode amplifier **202** comprising a stack of at least two serially-connected FETs **M1-Mn** is configured to receive an RF input signal, **RFIN**, either at a first node **1** coupled to the gate of **M1**, or at a second node **2** coupled to the source of **M1**. As used in this description, the term “RF” particularly includes frequencies from about **100** MHz and above. Applying the RF input signal to the source of a common gate amplifier (i.e., at the second node **2**) usually offers input impedances that are conducive to a simple, broadband input match. The source of **M1** may be coupled thorough a degeneration inductor **Ldeg** to RF ground. As noted above, the degeneration inductor **Ldeg**, which will also have an inherent resistance **Rdeg** (shown in dotted outline), performs several functions, including obtaining a good dynamic range (e.g., a good noise figure), achieving high sensitivity with low power consumption, and helping with input impedance matching. The drain of the top (last) FET **Mn** in the cascode amplifier **202** provides an amplified RF output signal, **RFOUT**.

[0041] As noted above, one drawback to silicon-based CMOS devices for amplifier applications, and particularly for power amplifier applications, is a relatively low breakdown voltage per device. One circuit configuration that overcomes the breakdown voltage liability associated with silicon-based CMOS devices is referred to as device “stacking”, in which the total RF voltage swing occurring across a circuit is distributed over two or more serially-connected (i.e., “stacked”) CMOS devices. Accordingly, as illustrated, the cascode amplifier **202** may be configured with **n** serially-connected FETs **M1-Mn** such that a particularly voltage level can be withstood without subjecting any of the constituent FETs to a voltage exceeding its breakdown voltage.

[0042] A cascode reference circuit **204** comprising a stack of at least two serially-connected FETs **Mb1-Mbn** is configured such that the gate of **Mb1** is coupled to the gate of **M1**, and the gate of **Mb2** is coupled to the gate of **M2**. Accordingly, any bias voltage **Vg1** applied to **M1** will be essentially the same as the bias voltage **Vgb1** applied to **Mb1**, and any bias voltage **Vg2** applied to **M2** will be essentially the same as the bias voltage **Vgb2** applied to **Mb2**. (Note that in many applications, each FET gate may include a corresponding gate resistor and gate capacitor, not shown for clarity; the gate capacitor sets up the RF voltage division in the stack and the resistor is used to isolate the RF signal from the DC bias circuit). As with the cascode amplifier **202**, the

cascode reference circuit **204** may be configured with a stack of n serially-connected FETs such that a particularly voltage level can be withstood without subjecting any of the constituent FETs to a voltage exceeding its breakdown voltage. The purpose of the cascode reference circuit **204** is to essentially act as a current mirror that sees bias voltages similar to the cascode amplifier **202**, with the devices in the cascode reference circuit **204** being scaled-down replicas of the devices in the cascode amplifier **202**. For example, if the devices in the cascode reference circuit **204** are 1/100 of the size of the devices in the cascode amplifier **202**, the scaling factor m would be 100. (The size of such devices may be defined in terms of transistor area, gate length, gate width, etc., so long as the same aspect is compared; using gate length as a metric, it is particularly useful to fabricate the FETs in the cascode amplifier **202** and the cascode reference circuit **204** with gate lengths that are less than about 1 μm). The FET device stacking in the cascode reference circuit **204** replicates the bias voltages in the cascode amplifier **202** stack, thus resulting in a more accurate current mirror. [0043] In general, the gate of each serially-connected FET M_2 - M_n in the cascode amplifier **202** is coupled to a bias voltage V_{g2} - V_{gn} , and the gate of each FET M_{b2} - M_{bn} in the cascode reference circuit **204** is coupled to a bias voltage V_{gb2} - V_{gbn} . In each case, the corresponding gate bias voltage generally will be a value derived from the system DC voltage $V_{\text{sub.DD}}$, for example, through a shared resistive voltage divider or through corresponding dedicated resistive voltage dividers. However, in some embodiments, the bias voltage V_{g2} - V_{gn} for one or more of FETs M_2 - M_n in the cascode amplifier **202** may be essentially the same as the bias voltage V_{gb2} - V_{gbn} applied to the gates of the corresponding FETs M_{b2} - M_{bn} in the cascode reference circuit **204**, such as by directly connected corresponding gates in the two circuits through an isolating filter (e.g., an RC filter).

[0044] To avoid unnecessary complication, the remainder of this disclosure will focus on the biasing to the bottom two stages of the cascode amplifier **202** and the cascode reference circuit **204**. Because of the cascode architecture of the bottom two stages M_1 , M_2 of the cascode amplifier **202**, biasing of those two stages controls the amplification properties of the amplifier circuit **200**. As illustrated, the gates of M_2 in the cascode amplifier **202** and M_{b2} in the cascode reference circuit **204** are both biased by a power source **206** derived from $V_{\text{sub.DD}}$. While nominally having a fixed voltage in some applications, $V_{\text{sub.DD}}$ may in fact exhibit a wide range of variability, intentionally or unintentionally, which would change all bias points in the cascode amplifier **202** and the cascode reference circuit **204**. For example, a system incorporating the illustrated amplifier circuit **200** may utilize average power tracking (APT), or envelope tracking (ET), or a GSM power amplifier with drain control of the output power. In APT mode, $V_{\text{sub.DD}}$ is typically modulated (e.g., by a DC-DC converter). In general, $V_{\text{sub.DD}}$ may range from about 0.4V to about 4.5V (thus, the bias voltages V_{g2} - V_{gn} will normally be in the same range). To save power in a system, V_{DD} may be set low (e.g., 0.4-1.0V) when little power is required in the cascode amplifier **202**, such as when low power levels are being transmitted. Conversely, V_{DD} may be set high (e.g., 4.2V) when higher power is required in the cascode amplifier **202**, such as during periods of signal transmission. With APT, the average power typically varies over seconds or tens of seconds. ET mode sets V_{DD} as a function of the signal modulation and accordingly V_{DD} may vary at a microsecond or faster rate. In light of the actual voltage variation that may be present, whether intentional or unintentional, the power source **206** is shown as including a gray arrow to indicate variability (usually intentionally; it is difficult to precisely control the bias voltage as some function of the supply voltage or hold it constant depending on how the amplifier is designed to operate (.

[0045] Thus, a design challenge is to provide a suitable control circuit for the cascode reference circuit **204** that accommodates arbitrary variations in its supply voltages. In addition, a bias circuit for the multi-stage cascode amplifier **202** must be designed to handle the low device output resistance of silicon-based CMOS devices with short channel lengths.

[0046] To satisfy this design challenge, embodiments of the invention utilize the cascode reference circuit **204** to bias the final stages of the cascode amplifier **202** under the control of a closed loop

bias control circuit **208**. The closed loop bias control circuit **208** is connected to the cascode reference circuit **204** in such a way as to receive feedback of varying voltages and/or currents in the cascode reference circuit **204**. The closed loop bias control circuit **208** utilizes such feedback to ensure that a current, I_{mirror} , in the cascode reference circuit **204** is approximately equal to a selected multiple of a known current value, I_{ref} , by adjusting the gate bias voltage V_{g1} , V_{gb1} to the final stage **M1** of the cascode amplifier **202** and the final stage **Mb1** of the cascode reference circuit **204**. The final current, I_{final} , through the cascode amplifier **202** is a multiple of I_{mirror} , based on the device scaling factor m representing the size of the transistor devices in the cascode amplifier **202** versus the size of the transistor devices in the cascode reference circuit **204**. For example, if I_{mirror} is about 100 μA , and m equals 1000, then I_{final} would be about 100 mA. More generally, I_{ref} is a reference current that may be used to generate a current I_{mirror} that flows through the mirror devices. Since I_{ref} is a generic reference current, its presence (and the circuitry for generating it) is implied in the generation of I_{mirror} in the figures described below, if not shown explicitly.

[0047] As described in greater detail below, there are a number of ways of implementing the closed loop bias control circuit **208** to control I_{mirror} , and thus I_{final} , while allowing for arbitrary variations in supply voltage. In addition, some embodiments include circuitry for force matching drain-source voltages as well as of gate voltages in the cascode amplifier **202**, in order to improve bias current mirroring accuracy.

[0048] An advantage of using a cascode reference circuit **204** to provide biasing to the cascode amplifier **202** is that corresponding drain voltages in the bottom stages (where the bottom stage of the cascode amplifier **202** is coupled to the RF input, as shown in FIG. 2A) of the two circuits can be forced to match in order to compensate for the poor output resistance of the FETs in the cascode reference circuit **204**, whereas a simple mirror bias circuit lacks that characteristic.

Additional Amplifier Circuit Elements

[0049] As should be apparent to one of skill in the art, the illustrated amplifier circuit **200** in FIG. 2A is highly simplified. In practical circuits, additional elements may be included for proper operation as an RF amplifier, such as bypass capacitors, filters, current sources, gate capacitors for RF voltage division, bias circuits such as bandgaps and such to generate the reference current, etc. As further examples, FIG. 2B is a more detailed amplifier circuit **250** showing some additional elements that may be added to the amplifier circuit **200** of FIG. 2A.

[0050] In some applications, the input signal RFIN may be first processed through an input impedance matching network (IIMN) **252**. FIG. 2C is a schematic diagram of one embodiment of an input impedance matching network **252** that may be used in conjunction with the circuit of FIG. 2B. As illustrated, the IIMN **252** may comprise a series-connected inductor L and a DC-blocking capacitor C . As should be clear to one of ordinary skill, other input impedance matching networks may be used to achieve particular performance specifications.

[0051] Similarly, in some applications, the output signal RFOUT may be first processed through an output impedance matching network (OIMN) **254**. FIG. 2D is a schematic diagram of one embodiment of an output impedance matching network **254** that may be used in conjunction with the circuit of FIG. 2B. As illustrated, the OIMN **254** may comprise a tank circuit (comprising an inductor L and first capacitor $C1$ coupled in parallel in this example) connected to a second capacitor $C2$. As should be clear to one of ordinary skill, other output impedance matching networks may be used to achieve particular performance specifications.

[0052] In some applications, de-coupling networks (DCN) **256A**, **256B** may be inserted between the gates of **Mb1**, **Mb2** of the cascode reference circuit **204** and the corresponding gates of **M1**, **M2** of the cascode amplifier **202** to isolate the cascode reference circuit **204** from RFIN (particularly if RFIN is coupled to node 1). As one example, a DCN **256A**, **256B** may comprise an RC, LC, RL, or RLC circuit coupled between the gates of corresponding FETs (e.g., **Mb1** and **M1**, or **Mb2** and **M2**). For example, an RC circuit may include a high-value resistor (e.g., at least about 2k ohms)

coupled between the gates of corresponding FETs, plus a shunt capacitor coupled to RF ground. Note that the DCNs **256A**, **256B** need not be identical in architecture or component values, and that additional DCNs may be used if the gates of higher stage FETs in both the cascode amplifier **202** and the cascode reference circuit **204** are connected in common.

[0053] As another example, a DCN **256A**, **256B** may comprise only a high-value resistor coupled between the gates of corresponding FETs, since there is no current into the gates. Alternatively, a DCN **256A**, **256B** may include a switchable network of resistors that allows selection of two or more different resistance values, where selection may be permanent (e.g., a mask-level selection during manufacture, or a fusible link setting in the field) or programmable. FIG. 2E is a schematic diagram of one embodiment of a switchable resistance de-coupling network **256x** that may be used in conjunction with the circuit of FIG. 2B. A first resistor **R1** is coupled in parallel with a series-connected second resistor **R2** and switch **Sw**; the switch **Sw** may be, for example, permanently configurable (e.g., a mask-level selection during manufacture, or a fusible link setting in the field) or a software-controlled FET. With switch **Sw** set to “OPEN” (i.e., non-conducting or OFF), the total resistance of the illustrated DCN would be **R1**; with switch **Sw** set to “CLOSED” (i.e., conducting or ON), the total resistance of the DCN would be equal to $R1 \times R2 / (R1 + R2)$. As should be clear, a switchable resistor network may provide more than two resistance levels (e.g., by including additional parallel switch/resistor pairs), and may be used in an R, RC, RL, or RLC de-coupling network circuit configuration.

[0054] In some applications, it is useful to compensate for the DC resistance in the inductor **Ldeg** (as represented by **Rdeg**) by inserting a compensation resistor **Rcomp** between RF ground and the source of **Mb1** in the cascode reference circuit **204**. The value of the compensation resistor **Rcomp** may be set to a multiple of **Rdeg** such that the voltage at the source of **Mb1** closely approximates the voltage at the source of **M1**. Inserting a compensation resistor **Rcomp** may be done so that the operating conditions of the mirror device and amplifier device are as equal as possible for accurate mirroring of current.

[0055] It may be desirable to fabricate the compensation resistor **Rcomp** as a metal resistor so that the temperature coefficients and relative tolerances of the inductor **Ldeg** and the compensation resistor **Rcomp** essentially match. More particularly, during IC fabrication, **Ldeg** may be created with a spiral metal path, while **Rcomp** may be created with a serpentine or meandering metal path. Since **Ldeg** and **Rcomp** would be constructed from similar materials, they would have similar temperature coefficients and thus maintain essentially the same resistance values with respect to temperature changes. Even if **Ldeg** and **Rcomp** were constructed of different metals (e.g., aluminum for one, copper for the other), the temperature coefficients generally would be comparable. In contrast, if **Ldeg** and **Rcomp** were constructed from significantly different materials (e.g., implanted poly for **Rcomp**, metal for **Ldeg**), they would have much different temperature coefficients and thus vary significantly in resistance as the temperature changed.

[0056] When a reference current source is specified, it may be implemented with a bandgap voltage reference across a resistor to generate a specified reference current. A bandgap voltage reference is a temperature independent voltage reference circuit widely used in integrated circuits, and produces an essentially constant voltage regardless of power supply variations, temperature changes, and circuit loading.

[0057] It may be noted also that in some integrated circuit embodiments, the gates of FETs **M1** and **M2** are merged, and thus there is no accessible contact between the devices (node **3** in FIG. 2B), which essentially prevents being able to monitor or sense the actual voltage at that node, thus limiting the types of circuits that may be used for the closed loop bias control circuit **208**.

Bias Control Circuit Embodiments—General Comments

[0058] Various embodiments of closed loop bias control circuits are described in the following sections referencing FIG. 3 through FIG. 8. In each case, for clarity, the cascode amplifier **202** is represented as a simplified rectangular component with only the bias inputs **Vg1**, **Vg2** for the

bottom two stages of n stages explicitly shown, and the figures omit RFIN, RFOUT, and the additional elements shown in FIGS. 2B-2E and/or described above. The cascode reference circuit **204** is shown with a stack height of two, but additional FETs may be serially connected to increase the stack height to handle the applied supply voltages, as described above. Further, when the mirror current circuitry is shown connected to $V_{sub,DD}$, alternatively such circuitry may be connected to another power supply, such as an internally regulated supply.

First Bias Control Circuit Embodiment

[0059] FIG. 3 is a simplified schematic diagram of an amplifier circuit **300** having a cascode reference circuit **204** configured with a first closed loop bias control circuit. The closed loop bias control circuit **208** of FIG. 2A may be simply implemented as a connection between a current source I_{mirror} applied to the drain of FET Mb2 and the gate of FET Mb1 of the cascode reference circuit **204**, thereby connecting Mb1 in a diode configuration. In this configuration, the cascode amplifier **202** and the cascode reference circuit **204** share common bias voltages for the bottom two stages (where “bottom” means the stage of the cascode amplifier **202** coupled to the RF input, as shown in FIG. 2A). Thus, the drain voltages of the bottom devices in each circuit, M1, Mb1, should match, thereby improving current mirroring accuracy in the cascode amplifier **202**. Because of the stacked architecture of a cascode amplifier **202** (at least two series-connected devices), the architecture is better suited to handle practical supply voltages, particularly when using silicon-based CMOS devices.

[0060] In operation, the current source I_{mirror} will force current into the stack of Mb2 and Mb1 by adjusting the gate voltage V_{gb1} until the full value of the current, I_{mirror} , is delivered through the stack of FETs in the cascode reference circuit **204**. This will occur to a large extent as the cascode bias V_{gb2} varies. The current in the cascode reference circuit **204** will be mirrored into the cascode amplifier **202** as I_{final} : $I_{final} = m * I_{mirror}$ (where m is the device scaling factor, as described more generally above). The accuracy with which the mirroring occurs depends on the device ratio, layout matching, and other physical parameters, as well as on the gate, source, and drain voltages of the reference FET Mb1 and corresponding amplifier device M1 being essentially equal (perfectly equal, in the ideal case). The inclusion of the cascode FET Mb2 and the equivalent FET M2 in the cascode amplifier **202** help keep the drain voltages on the bottom devices Mb1, M1, equal. If the FET output resistances of the bottom two FETs of the cascode amplifier were ideal (i.e., essentially infinite), one would simply have to match the gate and source voltages of those devices. However, due to the poor output resistance of the actual devices, the currents do not match if the drain voltages do not match each other exactly. Accordingly, the cascode reference circuit **204** is included to force the drain voltages to match. Again, because of poor device output resistance, it may be important to match other gate, source, and drain voltages in the stack to ensure current matching (and possibly the drain voltages higher in the two stacks as well).

Second Bias Control Circuit Embodiment

[0061] FIG. 4 is a simplified schematic diagram of an amplifier circuit **400** having a cascode reference circuit **204** configured with a second closed loop bias control circuit. The closed loop bias control circuit **208** of FIG. 2A is implemented by including a source follower FET M.sub.SF to drive (i.e., bias) the gates of the bottom stage devices, M1, Mb1. A bias current source I_{mirror} is coupled to the cascode reference circuit **204** as shown. With respect to FET M.sub.SF, its drain is coupled to $V_{sub,DD}$, its gate is coupled to the drain of Mb2, and its source is coupled to a bias current source I_{bias} and to the gates of M1 and Mb1. Accordingly, FET M.sub.SF supplies the bias voltages V_{g1} and V_{gb1} to the gates of M1 and Mb1, respectively. The source follower M.sub.SF also adds a voltage offset from the drain of Mb2 to the gate of Mb1; additional diode offsets or source follower devices may be added for an increased voltage offset.

[0062] The illustrated amplifier circuit **400** operates in a similar manner to the circuit in FIG. 3, except that use of the source follower helps increase the drain voltage seen on Mb2, which may in many cases more closely mimic the voltage seen by the equivalent device M2 in the cascode

amplifier **202**.

Third Bias Control Circuit Embodiment

[0063] FIG. **5** is a simplified schematic diagram of an amplifier circuit **500** having a cascode reference circuit **204** configured with a third closed loop bias control circuit. In this embodiment, the closed loop bias control circuit **208** of FIG. **2A** is implemented as an operational amplifier (op-amp) **502** having one input coupled to the drain of FET Mb2, while the other input is coupled between a first resistor R1 coupled to VDD and a reference current source I_{ref}. A second resistor R2 is coupled to the drain of Mb2; current I_{mirror} flows through R2 to the cascode reference circuit **204**. The output of the op-amp **502** is coupled as the bias voltages Vg1 and Vgb1 to the gates of M1 and Mb1, respectively.

[0064] In operation, the op-amp **502** actively responds to differences in its inputs by varying the bias voltages Vg1 and Vgb1 to the gates of M1 and Mb1 to adjust the current I_{mirror} through the reference device stack **204** so that the voltage drop across R1 equals the voltage drop across R2. Simultaneously, the drain voltages of M1 and Mb1 are confined to be the same by the common gate bias connection to M2 and Mb2. This results in the current I_{mirror} being a function of the reference current I_{ref}, such that the ratio I_{mirror}/I_{ref} equals R1/R2. The control loop keeps the drain voltage of the cascode reference circuit **204** mirror stack equal to $V_{sub,DD} - I_{ref} \cdot R1$. This is beneficial because it means the drain voltage can be controlled by setting selected values for R1, R2, and I_{ref}.

[0065] Another benefit of the illustrated embodiments is that the drain voltage of the cascode reference circuit **204** may be adjusted as a function of temperature, supply voltage, or other factors by a suitable choice of I_{ref}, R1, and/or R2. As should be clear, R1 and/or R2 may be fabricated so as to have selectable values (e.g., via a mask-level selection during manufacture, or a fusible link setting in the field) or programmable values.

Fourth Bias Control Circuit Embodiment

[0066] FIG. **6** is a simplified schematic diagram of an amplifier circuit **600** having a cascode reference circuit **204** configured with a fourth closed loop bias control circuit. This embodiment operates on essentially the same principle as the amplifier circuit **500** of FIG. **5**, but using current sources I_{mirror}, I_{bias} rather than resistors. More particularly, an op-amp **602** has one input coupled to the drain of FET Mb2, while the other input is coupled between a reference current source I_{bias} and a resistor R coupled to RF ground. The output of the op-amp **502** is coupled as the bias voltages Vg1 and Vgb1 to the gates of M1 and Mb1, respectively. The desired drain voltage for Mb2 is set by the value of $R \cdot I_{bias}$. The closed loop circuit works to keep the drain voltage of Mb2 equal to $R \cdot I_{bias}$ while adjusting Vgb1 until the drain voltage condition is met and the cascode reference stack **204** conducts a current equal to I_{mirror}.

Fifth Bias Control Circuit Embodiment

[0067] FIG. **7** is a simplified schematic diagram of an amplifier circuit **700** having a cascode reference circuit **204** configured with a fifth closed loop bias control circuit. A bias current source I_{bias} is coupled to the cascode reference circuit **204** as shown. The illustrated amplifier circuit **700** uses a voltage offset circuit between the drain of Mb2 and the gate of Mb1, rather than using an op-amp to close the control loop. Among other ways, the voltage offset circuit may be realized using series-connected current sources I₁ and I₂ and a resistor R (also connected to the drain of Mb2) to provide a voltage at node A that is coupled to the gate of a source follower FET M_{sub}.SF. The source follower M_{sub}.SF, coupled as shown between V_{sub}.DD and a current source I_{mirror}, as well as to the gates of M1 and Mb1, behaves as a buffer to allow somewhat arbitrary choices of resistor values and current sources, and is responsible for driving the gates of the bottom stage devices M1, Mb1.

[0068] The illustrated amplifier circuit **700** operates in a similar manner to the circuit in FIG. **4**, except that the current sources I₁, I₂ and the resistor R essentially act as a “virtual battery” or voltage source that increases the voltage between the drain of Mb2 and the gate of the source

follower Msf, which is useful in controlling the drain voltage of Mb2.

Sixth Bias Control Circuit Embodiment

[0069] FIG. 8 is a simplified schematic diagram of an amplifier circuit **800** having a “split” cascode reference circuit **204** configured with a sixth closed loop bias control circuit. The illustrated circuit splits FETs Mb1 and Mb2 so that there are not series connected. (Technically, the reference circuit is not cascaded, since the cascode elements are split into two separate circuits. However, the “split” cascode reference circuit is designed to mimic/track the voltages seen in a cascode circuit and supplies bias voltages to the cascode amplifier **202** in a manner similar to the true cascode reference circuits shown in the embodiments described above, and as described in greater detail below. Accordingly, the “split” cascode reference circuit is referred to here as simply a “cascode reference circuit **204**”).

[0070] FET Mb1 is coupled between a first reference current source **801a** providing a current I_{mirror} and RF ground; FET Mb2 is coupled between a second current source **801b** providing the same current I_{mirror} and V.sub.DD. An op-amp **802** has one input coupled to the drain of FET Mb1, while the other input is coupled to the source of FET Mb2 and to the current source I_{mirror} . The output of the op-amp **802** is coupled as the bias voltages Vg1 and Vgb1 to the gates of M1 and Mb1, respectively.

[0071] In operation, the op-amp **802** actively responds to differences in its inputs by varying the gate bias voltages Vg1, Vgb1 such that the current I_{mirror} through FET Mb1 equals the current I_{mirror} through FET Mb2. This circuit effectively splits a cascode into two pieces and uses the op-amp **802** to equalize the circuits. FET Mb2, coupled to FET M2, acts as the cascode device. The source voltage of FET Mb2 ideally represents the voltage at the source of FET M2 and the drain of FET M1 in the cascode amplifier **202** (i.e., node 3 in FIG. 2B), which ideally should match the drain voltage of the reference FET Mb1. The op-amp **802** adjusts the gate bias voltage Vgb1 so that the drain voltage of the reference FET Mb1 matches the drain voltage of FET M1 in the cascode amplifier **202** when $I_{\text{final}} = m \cdot I_{\text{mirror}}$.

[0072] The amplifier circuit **800** optionally may include a buffer circuit **804** (shown in dotted outline) to drive the gate voltage and associated capacitance of FETs Mb1 and M1. If present, the buffer circuit **804** may be configured like the source follower M.sub.SF buffer circuit of FIG. 7.

Digitally Programmable Bias

[0073] In some applications, it is useful to programmatically set a bias level such that the biased current through the cascode amplifier **202** can be adjusted by software control during operation. A digitally programmable bias level enables controlling performance metrics for various operational scenarios, and provides two main benefits that are not possible with a static fixed bias. First, a programmable bias level allows for design optimization of a product after fabrication. This simplifies design by reducing the need for precise bias design pre-fabrication with the confidence that the final product can be adjusted to meet specifications. Post-fabrication optimization also allows for the same product to be adjusted to meet different specifications, thus allowing one product to meet multiple demands with very fast time to market. Second, a programmable bias level allows for dynamically changing bias (and thus performance) during operation. This allows for better performance (where a static bias may underperform) and/or efficient performance (where a static bias may be wasteful and over-perform). In many applications, a software-based approach to adjusting bias is preferable to a physical approach such as varying the external bias voltage applied to the product.

[0074] One way of programmatically setting bias levels is to include a software switchable resistance de-coupling network (DCN) similar to the circuit shown in FIG. 2E. Selecting either [0075] R1 or $R1 \parallel R2$ in such a DCN would adjust how fast the circuit reacts. For example, selecting a higher value resistance (e.g., only R1) for the DCN **256B** in FIG. 2B better isolates the cascode reference circuit **204** from the cascode amplifier **202** so that the impedance seen by the RF input signal, RFIN, is more isolated from the cascode amplifier **202**, and noise from the cascode

reference circuit **204** to the cascode amplifier **202** is reduced. However, a high value resistance increases DC settling time. Programmatically selecting a lower value resistance (e.g., $R1 \parallel R2$) for the DCN during a transition operating period allows the cascode amplifier **202** to quickly adapt to the new condition. The DCN can be programmatically switched back to a higher value resistance during a static operating period.

[0076] In an alternative configuration, a DCN similar to the circuit shown in FIG. **2E** may be settable to one of several selectable resistance values. For example, by making the switch Sw a fusible link, the default resistance would be $R1 \parallel R2$. Blowing the link post-fabrication would allow the resistance to be changed to $R1$. Other techniques may be used for permanently selecting the configuration of such a DCN, such as by a grounding or voltage pin or pad for a FET switch, or a wire-bonding connection option.

[0077] In either case, as noted above, a switchable network DCN may provide more than two resistance levels (e.g., by including additional parallel switch/resistor pairs), and may be used in an R, RC, RL, or RLC de-coupling network circuit configuration.

[0078] In other embodiments, one or more of the current sources in the cascode reference circuit **204** may be programmable or settable current sources, such as current digital-to-analog converters (DACs). Selectable current output levels allow programmatic setting of bias levels.

Alternatives

[0079] As should be apparent from the above descriptions of cascode reference circuits configured with a closed loop bias control circuit, there are many possible variations to this circuit concept. However, a common basic concept is using a control loop to ensure that the current in a cascode reference circuit is approximately equal to a selected multiple of a known current value by adjusting the gate bias voltage to the bottom stage of a cascode amplifier, such that the mirrored final current through the cascode amplifier is a multiple of the current in the cascode reference circuit. Another common basic concept is matching the corresponding drain voltages of the bottom stages of the cascode amplifier and the cascode reference circuit in order to provide better current mirroring accuracy.

[0080] Stated another way, the invention encompasses an amplifier circuit including: a cascode amplifier having at least two serially connected FET stages; a cascode reference circuit having at least two serially connected FET stages, the gates of the last two stages being coupled to the corresponding gates of the last two stages of the cascode amplifier, for biasing the cascode amplifier to output a final current approximately equal to a multiple of a mirror current in the cascode reference circuit; and a closed loop bias control circuit, having at least one input coupled to the cascode reference circuit and an output coupled to the gates of the last stage of the cascode amplifier and of the cascode reference circuit, responsive to variations in voltage and/or current in the cascode reference circuit to output an adjustment gate bias voltage applied to the last stage of the cascode amplifier and of the cascode reference circuit that forces the mirror current in the cascode reference circuit to be approximately equal to a selected multiple of a known reference current value.

Methods

[0081] Another aspect of the invention includes biasing the final stages of a cascode amplifier under the control of a closed loop bias control circuit. For example, FIG. **9** is a flowchart **900** showing one method for automatically biasing the final stages of a cascode amplifier. The method includes providing a cascode amplifier having at least two serially connected field effect transistor (FET) stages, each FET stage having a gate, a drain, and a source, the bottom FET stage having an input configured to be coupled to an RF input signal to be amplified, and the top FET stage of the cascode amplifier having an output for providing an amplified RF input signal (STEP **902**); providing a cascode reference circuit having at least two serially connected FET stages, each FET having a gate, a drain, and a source, the gates of the bottom two FET stages of the cascode reference circuit being coupled to the corresponding gates of the bottom two FET stages of the

cascode amplifier, for biasing the cascode amplifier to output a final current approximately equal to a multiple of a mirror current in the cascode reference circuit (STEP 904); and automatically adjusting a gate bias voltage applied to the respective gates of the bottom FET stage of the cascode amplifier and of the cascode reference circuit in response to variations in voltage and/or current in the cascode reference circuit so as to force the mirror current in the cascode reference circuit to be approximately equal to a selected current value (STEP 906).

[0082] Yet another aspect of the invention includes alternative methods for biasing the final stages of a cascode amplifier, including: [0083] providing a cascode amplifier having at least two serially connected field effect transistor (FET) stages, each FET stage having a gate, a drain, and a source, the bottom FET stage having an input configured to be coupled to an RF input signal to be amplified, and the top FET stage of the cascode amplifier having an output for providing an amplified RF input signal; providing a cascode reference circuit having at least two serially connected FET stages, each FET having a gate, a drain, and a source, the gates of the bottom two FET stages of the cascode reference circuit being coupled to the corresponding gates of the bottom two FET stages of the cascode amplifier, for biasing the cascode amplifier to output a final current approximately equal to a multiple of a mirror current in the cascode reference circuit; and coupling a current source to the drain of the top FET stage of the cascode reference circuit and to the respective gates of the bottom FET stages of the cascode reference circuit and the cascode amplifier; wherein the respective gates of the bottom FET stages of the cascode reference circuit and the cascode amplifier are responsive to variations in voltage in the cascode reference circuit such that the mirror current in the cascode reference circuit is forced to be approximately equal to a selected current value; [0084] providing a cascode amplifier having at least two serially connected field effect transistor (FET) stages, each FET stage having a gate, a drain, and a source, the bottom FET stage having an input configured to be coupled to an RF input signal to be amplified, and the top FET stage of the cascode amplifier having an output for providing an amplified RF input signal; providing a cascode reference circuit having at least two serially connected FET stages, each FET having a gate, a drain, and a source, the gates of the bottom two FET stages of the cascode reference circuit being coupled to the corresponding gates of the bottom two FET stages of the cascode amplifier, for biasing the cascode amplifier to output a final current approximately equal to a multiple of a mirror current in the cascode reference circuit; coupling a current source to the drain of the top FET stage of the cascode reference circuit; and providing a source follower FET having a gate, a drain, and a source, the drain of the source follower FET being coupled to a voltage source, the gate of the source follower FET being coupled to the drain of the top FET stage of the cascode reference circuit, and the source of the source follower FET being coupled to a bias current source and to the gates of the bottom FET stages of the cascode reference circuit and the cascode amplifier, the source follower FET being responsive to variations in voltage and/or current in the cascode reference circuit to output an adjustment gate bias voltage applied to the respective gates of the bottom FET stage of the cascode amplifier and of the cascode reference circuit that forces the mirror current in the cascode reference circuit to be approximately equal to a selected current value; [0085] providing a cascode amplifier having at least two serially connected field effect transistor (FET) stages, each FET stage having a gate, a drain, and a source, the bottom FET stage having an input configured to be coupled to an RF input signal to be amplified, and the top FET stage of the cascode amplifier having an output for providing an amplified RF input signal; providing a cascode reference circuit having at least two serially connected FET stages, each FET having a gate, a drain, and a source, the gates of the bottom two FET stages of the cascode reference circuit being coupled to the corresponding gates of the bottom two FET stages of the cascode amplifier, for biasing the cascode amplifier to output a final current approximately equal to a multiple of a mirror current in the cascode reference circuit; and providing an op-amp having a first and a second input and an output, the first input being coupled between a voltage source through a first resistor and a reference current source, the second input being coupled between the

voltage source through a second resistor and the drain of the top FET stage of the cascode reference circuit, the output being coupled to the respective gates of the bottom FET stages of the cascode reference circuit and the cascode amplifier, wherein the op-amp is responsive to differences between its first and second inputs and outputs an adjustment gate bias voltage applied to the respective gates of the bottom FET stage of the cascode amplifier and of the cascode reference circuit that forces the mirror current in the cascode reference circuit to be approximately equal to a selected current value; [0086] providing a cascode amplifier having at least two serially connected field effect transistor (FET) stages, each FET stage having a gate, a drain, and a source, the bottom FET stage having an input configured to be coupled to an RF input signal to be amplified, and the top FET stage of the cascode amplifier having an output for providing an amplified RF input signal; providing a cascode reference circuit having at least two serially connected FET stages, each FET having a gate, a drain, and a source, the gates of the bottom two FET stages of the cascode reference circuit being coupled to the corresponding gates of the bottom two FET stages of the cascode amplifier, for biasing the cascode amplifier to output a final current approximately equal to a multiple of a mirror current in the cascode reference circuit; and providing an op-amp having a first and a second input and an output, the first input being coupled between a reference current source and a resistor coupled to circuit ground, the second input being coupled between a mirror current source and the drain of the top FET stage of the cascode reference circuit, the output being coupled to the respective gates of the bottom FET stages of the cascode reference circuit and the cascode amplifier, wherein the op-amp is responsive to differences between its first and second inputs and outputs an adjustment gate bias voltage applied to the respective gates of the bottom FET stage of the cascode amplifier and of the cascode reference circuit that forces the mirror current in the cascode reference circuit to be approximately equal to a selected current value; [0087] providing a cascode amplifier having at least two serially connected field effect transistor (FET) stages, each FET stage having a gate, a drain, and a source, the bottom FET stage having an input configured to be coupled to an RF input signal to be amplified, and the top FET stage of the cascode amplifier having an output for providing an amplified RF input signal; providing a cascode reference circuit having at least two serially connected FET stages, each FET having a gate, a drain, and a source, the gates of the bottom two FET stages of the cascode reference circuit being coupled to the corresponding gates of the bottom two FET stages of the cascode amplifier, for biasing the cascode amplifier to output a final current approximately equal to a multiple of a mirror current in the cascode reference circuit; coupling a first current source to the drain of the top FET stage of the cascode reference circuit; providing a voltage offset circuit including a resistor series-connected between current sources I_1 and current source I_2 , the drain of the top FET stage of the cascode reference circuit being coupled between the resistor and the current source I_1 ; and providing a source follower FET having a gate, a drain, and a source, the drain of the source follower FET being coupled to a voltage source, the source of the source follower FET being coupled to a second current source and to the respective gates of the bottom FET stages of the cascode reference circuit and the cascode amplifier, and the gate of the source follower FET being coupled to the voltage offset circuit between the resistor and the current source I_2 , the source follower FET being responsive to variations in voltage and/or current in the cascode reference circuit to output an adjustment gate bias voltage applied to the respective gates of the bottom FET stage of the cascode amplifier and of the cascode reference circuit that forces the mirror current in the cascode reference circuit to be approximately equal to a selected current value; [0088] providing a cascode amplifier having at least two serially connected field effect transistor (FET) stages, each FET stage having a gate, a drain, and a source, the bottom FET stage having an input configured to be coupled to an RF input signal to be amplified, and the top FET stage of the cascode amplifier having an output for providing an amplified RF input signal; providing a split cascode reference circuit having at least two FET stages, each FET having a gate, a drain, and a source, the gates of the bottom two FET stages of the cascode reference circuit being coupled to the corresponding gates of the bottom two

FET stages of the cascode amplifier, for biasing the cascode amplifier to output a final current approximately equal to a multiple of a mirror current in the cascode reference circuit, the drain of the bottom FET stage of the cascode reference circuit being coupled to a first mirror current source and the source of the bottom FET stage of the cascode reference circuit being coupled to circuit ground, and the drain of the next-to-bottom FET stage of the cascode reference circuit being coupled to a voltage source and the source of the next-to-bottom FET stage of the cascode reference circuit being coupled to a second mirror current source; and providing an op-amp having a first and a second input and an output, the first input being coupled to the source of the next-to-bottom FET stage of the cascode reference circuit, the second input being coupled to the drain of the bottom FET stage of the cascode reference circuit, the output being coupled to the respective gates of the bottom FET stages of the cascode reference circuit and the cascode amplifier, wherein the op-amp is responsive to differences between its first and second inputs and outputs an adjustment gate bias voltage applied to the respective gates of the bottom FET stage of the cascode amplifier and of the cascode reference circuit that forces the mirror current in the cascode reference circuit to be approximately equal to a selected current value.

[0089] The above methods may further include: the corresponding drain voltages of the bottom FET stage of the cascode amplifier and the cascode reference circuit being approximately the same; the cascode reference circuit being a split cascode reference circuit; providing an input impedance matching network coupled to the input of the bottom FET stage and configured to be coupled to the RF input signal to be amplified; providing an output impedance matching network coupled to the output; providing a respective decoupling network coupled between corresponding gates of each of the bottom two FET stages of the cascode amplifier; at least one decoupling network including a programmable resistance element for varying bias levels to the coupled gates; coupling a degeneration inductor between the source of the bottom FET stage of the cascode amplifier and RF ground, the degeneration inductor having a resistance R_{deg} , and coupling a compensation resistor between the source of the bottom FET stage of the cascode reference circuit and RF ground, the compensation resistor having a resistance R_{comp} such that the voltage at the source of the bottom FET stage of the cascode reference circuit closely approximates the voltage at the source of the bottom FET stage of the cascode amplifier; the input to the bottom FET stage being coupled to the gate of the bottom FET stage; the input to the bottom FET stage being coupled to the source of the bottom FET stage; coupling a source voltage to the cascode amplifier and the cascode reference circuit, the source voltage having a range of about 0.4V to about 4.5V; coupling a bias voltage to the gates of the cascode amplifier, the bias voltage having a range of about 0.4V to about 4.5V; the RF input signal including frequencies from and above about 100 MHz; and fabricating the FETs in the cascode amplifier and in the cascode reference circuit with gate lengths less than about 1 μm .

Fabrication Technologies and Options

[0090] The term “MOSFET” technically refers to metal-oxide-semiconductors; another synonym for MOSFET is “MISFET”, for metal-insulator-semiconductor FET. However, “MOSFET” has become a common label for most types of insulated-gate FETs (“IGFETs”). Despite that, it is well known that the term “metal” in the names MOSFET and MISFET is now often a misnomer because the previously metal gate material is now often a layer of polysilicon (polycrystalline silicon). Similarly, the “oxide” in the name MOSFET can be a misnomer, as different dielectric materials are used with the aim of obtaining strong channels with smaller applied voltages. Accordingly, the term “MOSFET” as used herein is not to be read as literally limited to metal-oxide-semiconductors, but instead includes IGFETs in general.

[0091] As should be readily apparent to one of ordinary skill in the art, various embodiments of the invention can be implemented to meet a wide variety of specifications. Unless otherwise noted above, selection of suitable component values is a matter of design choice and various embodiments of the invention may be implemented in any suitable IC technology (including but not limited to MOSFET and IGFET structures), or in hybrid or discrete circuit forms. Integrated

circuit embodiments may be fabricated using any suitable substrates and processes, including but not limited to standard bulk silicon, silicon-on-insulator (SOI), silicon-on-sapphire (SOS), GaN HEMT, GaAs pHEMT, and MESFET technologies. However, the inventive concepts described above are particularly useful with an SOI-based fabrication process (including SOS), and with fabrication processes having similar characteristics. Fabrication in CMOS on SOI or SOS enables low power consumption, the ability to withstand high power signals during operation due to FET stacking, good linearity, and high frequency operation. Monolithic IC implementation is particularly useful since parasitic capacitances generally can be kept low (or at a minimum, kept uniform across all units, permitting them to be compensated) by careful design.

[0092] Voltage levels may be adjusted or voltage and/or logic signal polarities reversed depending on a particular specification and/or implementing technology (e.g., NMOS, PMOS, or CMOS, and enhancement mode or depletion mode transistor devices). Component voltage, current, and power handling capabilities may be adapted as needed, for example, by adjusting device sizes, serially “stacking” components (particularly FETs) to withstand greater voltages, and/or using multiple components in parallel to handle greater currents. Additional circuit components may be added to enhance the capabilities of the disclosed circuits and/or to provide additional functional without significantly altering the functionality of the disclosed circuits.

[0093] A number of embodiments of the invention have been described. It is to be understood that various modifications may be made without departing from the spirit and scope of the invention. For example, some of the steps described above may be order independent, and thus can be performed in an order different from that described. Further, some of the steps described above may be optional. Various activities described with respect to the methods identified above can be executed in repetitive, serial, or parallel fashion. It is to be understood that the foregoing description is intended to illustrate and not to limit the scope of the invention, which is defined by the scope of the following claims, and that other embodiments are within the scope of the claims. (Note that the parenthetical labels for claim elements are for ease of referring to such elements, and do not in themselves indicate a particular required ordering or enumeration of elements; further, such labels may be reused in dependent claims as references to additional elements without being regarded as starting a conflicting labeling sequence).

Claims

1. (canceled)

2. An amplifier circuit including: (a) a cascode amplifier including at least a first and a second field effect transistor (FET) stage connected in series, each FET stage including a gate, a drain, and a source, the first FET stage including an input configured to be coupled to a radio frequency (RF) input signal to be amplified, and the second FET stage of the cascode amplifier including an output for providing an amplified RF input signal; (b) a cascode reference circuit including at least a first and a second FET stage connected in series, each FET stage including a gate, a drain, and a source, the gates of the first and second FET stages of the cascode reference circuit being coupled to the corresponding gates of the first and second FET stages of the cascode amplifier; (c) a source follower FET including a gate, a drain, and a source, the drain of the source follower FET being configured to be coupled to a voltage source, the gate of the source follower FET being coupled to the drain of a top FET stage of the cascode reference circuit, and the source of the source follower FET being configured to be coupled to a bias current source and to the gates of the first FET stages of the cascode reference circuit and the cascode amplifier; and (d) a first decoupling network coupled between the gates of the second FET stages of the cascode amplifier and the cascode reference circuit, wherein the decoupling network includes a programmable resistance element for varying bias levels to the coupled gates.

3. The amplifier circuit of claim 2, wherein the corresponding drain voltages of the first FET stages

of the cascode amplifier and the cascode reference circuit are approximately the same.

4. The amplifier circuit of claim 2, further including an input impedance matching network coupled to the input of the first FET stage of the cascode amplifier and configured to be coupled to the RF input signal to be amplified.

5. The amplifier circuit of claim 2, further including an output impedance matching network coupled to the output of the cascode amplifier.

6. The amplifier circuit of claim 2, further including a second decoupling network coupled between corresponding gates of the first FET stages of the cascode amplifier and the cascode reference circuit.

7. The amplifier circuit of claim 6, wherein the second decoupling network includes a programmable resistance element for varying bias levels to the coupled gates.

8. The amplifier circuit of claim 2, further including: (a) a degeneration inductor coupled to the source of the first FET stage of the cascode amplifier and configured to be coupled to RF ground, the degeneration inductor including a first resistance; and (b) a compensation resistor coupled to the source of the first FET stage of the cascode reference circuit and configured to be coupled to RF ground, the compensation resistor having a resistance value such that the voltage at the source of the first FET stage of the cascode reference circuit closely approximates the voltage at the source of the first FET stage of the cascode amplifier.

9. The amplifier circuit of claim 2, wherein the input is coupled to the gate of the first FET stage of the cascode amplifier.

10. The amplifier circuit of claim 2, wherein the input is coupled to the source of the first FET stage of the cascode amplifier.

11. The amplifier circuit of claim 2, wherein the RF input signal includes frequencies from and above about 100 MHz.

12. An amplifier circuit including: (a) a cascode amplifier including at least a first and a second field effect transistor (FET) stage connected in series, each FET stage including a gate, a drain, and a source, the first FET stage including an input configured to be coupled to a radio frequency (RF) input signal to be amplified, and the second FET stage of the cascode amplifier including an output for providing an amplified RF input signal; (b) a cascode reference circuit including at least a first and a second FET stage connected in series, each FET stage including a gate, a drain, and a source, the gates of the first and second FET stages of the cascode reference circuit being coupled to the corresponding gates of the first and second FET stages of the cascode amplifier; (c) a first current source, coupled to the drain of a top FET stage of the cascode reference circuit; (d) a voltage offset circuit including a resistor configured to be coupled between a first current source and a second current source, the drain of a top FET stage of the cascode reference circuit being coupled between the resistor and the first current source; and (e) a source follower FET including a gate, a drain, and a source, wherein: (1) the drain of the source follower FET is configured to be coupled to a voltage source; (2) the source of the source follower FET is configured to be coupled to a third current source and to the respective gates of the first FET stages of the cascode reference circuit and the cascode amplifier; and (3) the gate of the source follower FET is coupled to the voltage offset circuit between the resistor and the second current source.

13. The amplifier circuit of claim 12, wherein the corresponding drain voltages of the first FET stages of the cascode amplifier and the cascode reference circuit are approximately the same.

14. The amplifier circuit of claim 12, further including an input impedance matching network coupled to the input of the first FET stage of the cascode amplifier and configured to be coupled to the RF input signal to be amplified.

15. The amplifier circuit of claim 12, further including an output impedance matching network coupled to the output of the cascode amplifier.

16. The amplifier circuit of claim 12, further including a respective decoupling network coupled between corresponding gates of each of the first and second FET stages of the cascode amplifier

and the cascode reference circuit.

17. The amplifier circuit of claim 16, wherein at least one decoupling network includes a programmable resistance element for varying bias levels to the coupled gates.

18. The amplifier circuit of claim 12, further including: (a) a degeneration inductor coupled to the source of the first FET stage of the cascode amplifier and configured to be coupled to RF ground, the degeneration inductor including a first resistance; and (b) a compensation resistor coupled to the source of the first FET stage of the cascode reference circuit and configured to be coupled to RF ground, the compensation resistor having a resistance value such that the voltage at the source of the first FET stage of the cascode reference circuit closely approximates the voltage at the source of the first FET stage of the cascode amplifier.

19. The amplifier circuit of claim 12, wherein the input is coupled to the gate of the first FET stage of the cascode amplifier.

20. The amplifier circuit of claim 12, wherein the input is coupled to the source of the first FET stage of the cascode amplifier.

21. The amplifier circuit of claim 12, wherein the RF input signal includes frequencies from and above about 100 MHZ.
