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### Noise filter circuit with controllable transistor off-resistance and associated noise filtering method

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#### Abstract

A noise filter circuit includes a filter and a transistor off-resistance control circuit. The filter includes a first transistor and a charge storage component. The first transistor has off-resistance when turned off or operated under sub-threshold region. A control terminal of the first transistor is not directly tied to a reference voltage, and is used to receive a first control voltage. The charge storage component has one terminal coupled to a connection terminal of the first transistor. The transistor off-resistance control circuit is coupled to the first transistor, and arranged to set the first control voltage for controlling the off-resistance of the first transistor.

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## Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS (1) This application claims the benefit of U.S. Provisional Application No. 63/347,601, filed on Jun. 1, 2022. The content of the application is incorporated herein by reference.

## BACKGROUND

- (1) The present invention relates to a filter design, and more particularly, to a noise filter circuit with controllable transistor off-resistance and an associated noise filtering method.
- (2) A reference generator is commonly used to provide a constant voltage as a bias voltage needed by a processing circuit such as a digital-to-analog (DAC) cell. To make the reference generator meet the low-noise requirements, large current dissipation or source-degeneration is needed to reduce the thermal and flicker noise. However, the reference generator with large current dissipation suffers from increased power consumption, and the reference generator with large source-degeneration suffers from limited headroom of supply voltage shrinking.
- (3) One typical solution is to add a low-pass filter at the output of the reference generator. However, the low-pass filter needs large resistance/capacitance for low corner frequency such as audio bandwidth (<20 Hz), which causes huge area consumption and cannot be implemented using on-chip resistor/capacitor. To address these issues, a sample-and-hold noise filter with a switch controlled by pulse-width modulation (PWM) pulses or a continuous-time noise filter with gate leakage variation compensation may be used. However, regarding the typical sample-and-hold noise with the switch controlled by PWM pulses, the control signal of the switch circuit will generate tones at low-frequency band that interferes with audio signals of an audio application. Regarding the typical continuous-time noise filter with gate leakage variation compensation, it suffers from slow settling time due to large time constant as well as large voltage variation at operational amplifier output caused by large transistor off-resistance. The slow settling time of the typical continuous-time noise filter exceeds the acceptable latency for an audio output. The typical continuous-time noise filter with large operational amplifier output is not applicable to low-voltage applications. In addition, leakage current of the transistor with large off-resistance also causes undesired mismatch between an input voltage and an output voltage of the noise filter. Thus, there is a need for an innovative noise filter which is capable of reducing the transistor off-resistance.

## SUMMARY

- (4) One of the objectives of the claimed invention is to provide a noise filter circuit with controllable transistor off-resistance and an associated noise filtering method.
- (5) According to a first aspect of the present invention, an exemplary noise filter circuit includes a filter and a transistor off-resistance control circuit. The filter includes a first transistor and a charge storage component. The first transistor is arranged to have off-resistance when turned off or operated under sub-threshold region, and comprises: a control terminal, arranged to receive a first control voltage, wherein the control terminal is not directly tied to a reference voltage; a first connection terminal; and a second connection terminal. The charge storage component has one terminal coupled to the second connection terminal of the first transistor. The transistor off-resistance control circuit is coupled to the first transistor, and arranged to set the first control voltage for controlling the off-resistance of the first transistor.
- (6) According to a second aspect of the present invention, an exemplary noise filtering method is disclosed. The exemplary noise filtering method includes: setting a control voltage at a control terminal of a transistor for controlling off-resistance of the transistor, wherein the control terminal of the transistor is not directly tied to a reference voltage; and performing a filtering operation upon an input voltage to generate an output voltage, wherein the filtering operation is based on the transistor and a charge storage component.
- (7) These and other objectives of the present invention will no doubt become obvious to those of

ordinary skill in the art after reading the following detailed description of the preferred embodiment that is illustrated in the various figures and drawings.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

- (1) FIG. 1 is a diagram illustrating one noise filter circuit according to an embodiment of the present invention.
- (2) FIG. 2 is a diagram illustrating another noise filter circuit according to an embodiment of the present invention.
- (3) FIG. 3 is a diagram illustrating a first transistor off-resistance control circuit according to an embodiment of the present invention.
- (4) FIG. 4 is a diagram illustrating a second transistor off-resistance control circuit according to an embodiment of the present invention.
- (5) FIG. 5 is a diagram illustrating a third transistor off-resistance control circuit according to an embodiment of the present invention.
- (6) FIG. 6 is a diagram illustrating a fourth transistor off-resistance control circuit according to an embodiment of the present invention.
- (7) FIG. 7 is a diagram illustrating a fifth transistor off-resistance control circuit according to an embodiment of the present invention.
- (8) FIG. 8 is a diagram illustrating a sixth transistor off-resistance control circuit according to an embodiment of the present invention.
- (9) FIG. 9 is a diagram illustrating a seventh transistor off-resistance control circuit according to an embodiment of the present invention.
- (10) FIG. 10 is a diagram illustrating an eighth transistor off-resistance control circuit according to an embodiment of the present invention.
- (11) FIG. 11 is a diagram illustrating a ninth transistor off-resistance control circuit according to an embodiment of the present invention.
- (12) FIG. 12 is a diagram illustrating a tenth transistor off-resistance control circuit according to an embodiment of the present invention.
- (13) FIG. 13 is a diagram illustrating an eleventh transistor off-resistance control circuit according to an embodiment of the present invention.
- (14) FIG. 14 is a diagram illustrating a twelfth transistor off-resistance control circuit according to an embodiment of the present invention.

### DETAILED DESCRIPTION

(15) Certain terms are used throughout the following description and claims, which refer to particular components. As one skilled in the art will appreciate, electronic equipment manufacturers may refer to a component by different names. This document does not intend to distinguish between components that differ in name but not in function. In the following description and in the claims, the terms “include” and “comprise” are used in an open-ended fashion, and thus should be interpreted to mean “include, but not limited to . . .”. Also, the term “couple” is intended to mean either an indirect or direct electrical connection. Accordingly, if one device is coupled to another device, that connection may be through a direct electrical connection, or through an indirect electrical connection via other devices and connections.

(16) FIG. 1 is a diagram illustrating one noise filter circuit according to an embodiment of the present invention. Byway of example, but not limitation, the noise filter circuit **100** may be employed by an audio application. The noise filter circuit **100** includes a filter **102**, a transistor off-resistance control circuit **104**, and a transistor body-biasing circuit **106**. It should be noted that the transistor body-biasing circuit **106** may be optional, depending upon actual design considerations.

In this embodiment, the filter **102** includes a transistor **M0** and a charge storage component (e.g., an on-chip capacitor) **108**. The transistor **M0** may be implemented by a P-channel metal-oxide-semiconductor (PMOS) transistor or an N-channel metal-oxide-semiconductor (NMOS) transistor, depending upon actual design considerations. The transistor **M0** is arranged to have off-resistance  $R_{off,0}$  when turned off or operated under sub-threshold region. For example, the filter **102** is configured to act as a low-pass filter such as a continuous-time low-pass filter, where the transistor **M0** is used to generate a large resistance with the off-resistance  $R_{off,0}$ . As shown in FIG. **1**, the transistor **M0** is a four-terminal device including a control terminal (e.g., a gate terminal) N.sub.0,1, two connection terminals (e.g., a source terminal and a drain terminal) N.sub.0,2, N.sub.0,3, and a body terminal N.sub.0,4. The control terminal (e.g., gate terminal) N.sub.0,1 is arranged to receive a control voltage (e.g., a gate voltage) that is intentionally set to turn off the transistor **M0**, thereby making the transistor **M0** act as a resistor with the off-resistance  $R_{off,0}$ . The body terminal N.sub.0,4 is arranged to receive a body voltage that is applied to the bulk/body/substrate of the transistor **M0** and can be controlled to affect a threshold voltage of the transistor **M0**. In this embodiment, the body voltage is provided by the transistor body-biasing circuit **106**. That is, the bulk/body/substrate of the transistor **M0** can be driven by the transistor body-biasing circuit **106**. The connection terminal N.sub.0,2 is arranged to receive an input voltage  $V_{IN}$  of the filter (e.g., low-pass filter) **102** from an input port IN of the noise filter circuit **100**. The connection terminal N.sub.0,3 is arranged to output an output voltage  $V_{OUT}$  of the filter (e.g., low-pass filter) **102** to an output port OUT of the noise filter circuit **100**. The charge storage component (e.g., on-chip capacitor) **108** has one terminal P\_top coupled to the connection terminal N.sub.0,3 of the transistor **M0**. It should be noted that the control terminal N.sub.0,1 is not directly tied to a reference voltage such as a supply voltage VDD or a ground voltage GND, and the control voltage is provided through the transistor off-resistance control circuit **104**. Hence, with the help of the proposed transistor off-resistance control circuit **104**, the control voltage at the control terminal N.sub.0,1 is controllable, such that the transistor **M0** with controllable off-resistance  $R_{off,0}$  can be achieved.

(17) In the embodiment shown in FIG. **1**, the transistor off-resistance control circuit **104** is arranged to control the off-resistance of only a single transistor (e.g., transistor **M0**). However, this is for illustrative purposes only, and is not meant to be a limitation of the present invention. In some embodiments of the present invention, a noise filter circuit may have more than one transistor that is turned off (or operated under sub-threshold region) to act as a resistor with the off-resistance. The proposed transistor off-resistance control circuit can be used to control the off-resistance of more than one transistor.

(18) FIG. **2** is a diagram illustrating another noise filter circuit according to an embodiment of the present invention. Byway of example, but not limitation, the noise filter circuit **200** may be employed by an audio application. The noise filter circuit **200** includes an operational amplifier **202**, a transistor off-resistance control circuit **204**, a transistor **M0'**, and the aforementioned filter (e.g., low-pass filter) **102** and transistor body-biasing circuit **106**. The transistor **M0** of the aforementioned filter **102** is located at a forward path **206**, while the transistor **M0'** is located at a feedback path **208**. It should be noted that the transistor body-biasing circuit **106** may be optional, depending upon actual design considerations. In addition, the transistor **M0** may be implemented by a PMOS transistor or an NMOS transistor, depending upon actual design considerations; and the transistor **M0'** may be implemented by a PMOS transistor or an NMOS transistor, depending upon actual design considerations. Like the transistor **M0**, the transistor **M0'** is arranged to have off-resistance  $R_{off,0'}$  when turned off or operated under sub-threshold region.

(19) The operational amplifier **202** has two input terminals and an output terminal, where one of the input terminals is a non-inverting input terminal (+) that is coupled to the input port IN of the noise filter circuit **200**, the other of the input terminals is an inverting input terminal (-) coupled to the feedback path **208**, and the output terminal is coupled to the forward path **206**. As shown in

FIG. 2, the transistor  $M0'$  is a four-terminal device including a control terminal (e.g., a gate terminal) N.sub.0',1, two connection terminals (e.g., a source terminal and a drain terminal) N.sub.0',2, N.sub.0',3, and a body terminal N.sub.0',4. The control terminal (e.g., gate terminal) N.sub.0',1 is arranged to receive a control voltage (e.g., a gate voltage) that is intentionally set to turn off the transistor  $M0'$ , thereby making the transistor  $M0'$  act as a resistor with the off-resistance  $R_{off,0'}$ . The body terminal N.sub.0',4 is arranged to receive a body voltage that is applied to the bulk/body/substrate of the transistor  $M0'$  and can be controlled to affect the threshold voltage of the transistor  $M0'$ . In this embodiment, the body voltage is also provided by the transistor body-biasing circuit 106. That is, the bulk/body/substrate of each of the transistors  $M0$  and  $M0'$  is driven by the same transistor body-biasing circuit 106. The connection terminal N.sub.0',2 is coupled to the inverting input terminal (-) of the operational amplifier 202. The connection terminal N.sub.0',3 is coupled to the connection terminal N.sub.0,3 of the transistor  $M0$ . It should be noted that the control terminal N.sub.0',1 is not directly tied to a reference voltage such as a supply voltage VDD or a ground voltage GND, and the control voltage is provided through the transistor off-resistance control circuit 204. The transistor off-resistance control circuit 204 is arranged to control off-resistance of both transistors  $M0$  and  $M0'$ . Hence, with the help of the proposed transistor off-resistance control circuit 204, the control voltages at the control terminals N.sub.0,1 and N.sub.0',1 are controllable, such that the transistor  $M0$  with controllable off-resistance  $R_{off,0}$  and the transistor  $M0'$  with controllable off-resistance  $R_{off,0'}$  can be achieved.

(20) As mentioned above, the transistor off-resistance control circuit 104/204 is arranged to set the control voltage (e.g., gate voltage) at the control terminal N.sub.0,1 (e.g., gate terminal) of the transistor (e.g., PMOS transistor or NMOS transistor)  $M0$  for controlling the off-resistance  $R_{off,0}$  of the transistor  $M0$ . In some embodiments of the present invention, the transistor off-resistance control circuit 104/204 may employ a replica transistor for achieving the objective of controlling the off-resistance  $R_{off,0}$  of the transistor  $M0$ .

(21) FIG. 3 is a diagram illustrating a first transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit 104/204 may be implemented using the transistor off-resistance control circuit 300. The transistor off-resistance control circuit 300 includes a transistor  $M1$  and may further include other circuit components (not shown), where the transistor  $M1$  is a replica of the transistor  $M0$ . Since the leakage current of the transistor  $M0$  that passes through the off-resistance  $R_{off,0}$  is small, the transistor  $M1$  may be implemented by a scaled replica  $N \times M0$  to facilitate the circuit design of the transistor off-resistance control circuit 300, where  $N$  is not restricted to be an integer. For example, the transistor  $M1$  may be implemented by a plurality of replica transistors connected in parallel. As shown in FIG. 3, the transistor  $M1$  is a four-terminal device including a control terminal (e.g., a gate terminal) N.sub.1,1, two connection terminals (e.g., a source terminal and a drain terminal) N.sub.1,2, N.sub.1,3, and a body terminal N.sub.1,4. In this embodiment, the control terminal (e.g., gate terminal) N.sub.1,1 of the transistor  $M1$  (which may be an NMOS transistor or a PMOS transistor) is directly connected to the control terminal (e.g., gate terminal) N.sub.0,1 of the transistor  $M0$  (which may be an NMOS transistor or a PMOS transistor). Hence, the control voltage generated at the control terminal (e.g., gate terminal) N.sub.1,1 of the transistor  $M1$  is mirrored to act as the control voltage at the control terminal (e.g., gate terminal) N.sub.0,1 of the transistor  $M0$ . With the help of the direct connection 302 routed between the control terminal N.sub.1,1 of the transistor  $M1$  and the control terminal N.sub.0,1 of the transistor  $M0$ , the off-resistance  $R_{off,0}$  of the transistor  $M0$  can be controlled by the transistor off-resistance control circuit 300 through setting the control voltage at the control terminal N.sub.1,1 of the transistor  $M1$ .

(22) FIG. 4 is a diagram illustrating a second transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit 104/204 may be implemented using the transistor off-resistance control circuit 400. The transistor off-resistance control circuit 400 includes an operational amplifier 402, the transistor  $M1$  and other circuit

components (not shown). The transistor **M1** is a replica of the transistor **M0**, and can be a scaled replica  $N \times M0$  to facilitate the circuit design of the transistor off-resistance control circuit **400**, where  $N$  is not restricted to be an integer. The major difference between the transistor off-resistance control circuits **300** and **400** is that the control terminal (e.g., gate terminal)  $N_{\text{sub.1,1}}$  of the transistor **M1** is connected to the control terminal (e.g., gate terminal)  $N_{\text{sub.0,1}}$  of the transistor **M0** via a buffer circuit that is implemented by the operational amplifier **402**. For example, the buffer circuit may be a unity-gain buffer (also called a unity-gain amplifier). As shown in FIG. 4, the operational amplifier **402** has a non-inverting input terminal (+) coupled to the control terminal (e.g., gate terminal)  $N_{\text{sub.1,1}}$  of the transistor **M1**, and has an output terminal coupled to the control terminal (e.g., gate terminal)  $N_{\text{sub.0,1}}$  of the transistor **M0** and an inverting input terminal (−) of the operational amplifier **402**. Hence, the control voltage generated at the control terminal (e.g., gate terminal)  $N_{\text{sub.1,1}}$  of the transistor **M1** is mirrored to act as the control voltage at the control terminal (e.g., gate terminal)  $N_{\text{sub.0,1}}$  of the transistor **M0**. With the help of the buffer circuit (e.g., unity-gain buffer) between the control terminal (e.g., gate terminal)  $N_{\text{sub.1,1}}$  of the transistor **M1** and the control terminal (e.g., gate terminal)  $N_{\text{sub.0,1}}$  of the transistor **M0**, the off-resistance  $R_{\text{off},0}$  of the transistor **M0** can be controlled by the transistor off-resistance control circuit **300** through setting the control voltage at the control terminal (e.g., gate terminal) of the transistor **M1**.

(23) The transistor off-resistance control circuit **300/400** may have circuit components needed to set the control voltage at the control terminal (e.g., gate terminal)  $N_{\text{sub.1,1}}$  of the replica transistor **M1**. FIG. 5 is a diagram illustrating a third transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit **104/204** may be implemented using the transistor off-resistance control circuit **500**, and the transistor body-biasing circuit **106** may be implemented using the transistor body-biasing circuit **502**. Regarding the transistor off-resistance control circuit **500**, it includes a bias voltage generator circuit **504**, the transistor **M1** (which is a replica of the transistor **M0**), an operational amplifier **508**, and a bias current generator circuit **512**. In this embodiment, the transistor **M1** is implemented by a PMOS transistor. The bias voltage generator circuit **504** is arranged to provide the connection terminal (i.e., source terminal)  $N_{\text{sub.1,2}}$  of the transistor **M1** (which is a PMOS transistor) with a bias voltage  $V_B$ . In this embodiment, the bias voltage generator circuit **504** includes an operational amplifier **506**, a transistor **MB**, and a voltage source **514**. The operational amplifier **506** has two input terminals (e.g., a non-inverting input terminal (+) and an inverting input terminal (−)) and an output terminal. The non-inverting input terminal (+) of the operational amplifier **506** is coupled to the connection terminal  $N_{\text{sub.0,2}}$  of the transistor **M0**, and the output terminal of the operational amplifier **506** is coupled to a control terminal (e.g., a gate terminal) of the transistor **MB**. The connection terminal  $N_{\text{sub.2,2}}$  of the transistor **MB** is arranged to receive a reference voltage (e.g., a supply voltage  $V_{DD}$ ), and the connection terminal  $N_{\text{sub.2,3}}$  of the transistor **MB** is coupled to the connection terminal (i.e., source terminal)  $N_{\text{sub.1,2}}$  of the transistor **M1** (which is a PMOS transistor). The voltage source **514** is coupled between the inverting input terminal (−) of the operational amplifier **506** and the connection terminal (i.e., source terminal)  $N_{\text{sub.1,2}}$  of the transistor **M1** (which is a PMOS transistor).

(24) The operational amplifier **508** has two input terminals (e.g., a non-inverting input terminal (+) and an inverting input terminal (−)) and an output terminal. The output terminal of the operational amplifier **508** is coupled to the control terminal (i.e., gate terminal) of the transistor **M1** (which is a PMOS transistor), the inverting input terminal (−) of the operational amplifier **508** is coupled to the connection terminal  $N_{\text{sub.0,2}}$  of the transistor **M0**, and the non-inverting input terminal (+) of the operational amplifier **508** is coupled to the connection terminal (i.e., drain terminal)  $N_{\text{sub.1,3}}$  of the transistor **M1** (which is a PMOS transistor). Hence, due to inherent characteristics of the operational amplifier **508**, the voltage at the connection terminal (i.e., drain terminal)  $N_{\text{sub.1,3}}$  of the transistor **M1** (which is a PMOS transistor) is similar to the voltage at the connection terminal

N.sub.0,2 of the transistor **M0**.

(25) The bias current generator **512** is arranged to provide the connection terminal (i.e., drain terminal) N.sub.1,3 of the transistor **M1** (which is a PMOS transistor) with a bias current  $I_B$ . In this embodiment, the bias current generator **512** is coupled between the connection terminal (i.e., drain terminal) N.sub.1,3 of the transistor **M1** (which is a PMOS transistor) and a reference voltage (e.g., a ground voltage GND). Hence, the bias voltage  $V_B$  at the connection terminal (i.e., source terminal) N.sub.1,2 of the transistor **M1** (which is a PMOS transistor) is configured to be higher than the voltage at the connection terminal (i.e., drain terminal) N.sub.1,3 of the transistor **M1** (which is a PMOS transistor), and the bias current  $I_B$  is configured to flow from the connection terminal (i.e., drain terminal) N.sub.1,3 of the transistor **M1** (which is a PMOS transistor) towards the reference voltage (e.g., ground voltage GND).

(26) In this embodiment, the off-resistance  $R_{off,1}$  of the transistor **M1** is defined by  $V_B/I_B$ . Since the control voltage (e.g., gate voltage) at the control terminal N.sub.1,1 of the transistor **M1** (which is a replica of the transistor **M0**, such as  $N \times M0$ ) is mirrored to act as the control voltage (e.g., gate voltage) at the control terminal N.sub.0,1 of the transistor **M0**, the off-resistance  $R_{off,0}$  of the transistor **M0** is defined by

(27)  $\frac{V_B}{I_B} \times N$ .

Hence, with proper settings of controllable bias voltage  $V_B$  and controllable bias current  $I_B$  at the transistor off-resistance control circuit **400**, controllable off-resistance  $R_{off,0}$  of the transistor **M0** can be achieved. For example, the off-resistance  $R_{off,0}$  of the transistor **M0** can be reduced to make the noise filter circuit **100/200** meet requirements of an application such as faster settling time, smaller operational amplifier output voltage, and smaller  $V_{OUT}/V_{IN}$  mismatch.

(28) The transistor **M1** is a replica of the transistor **M0**, and can be a scaled replica  $N \times M0$  to facilitate the circuit design of the transistor off-resistance control circuit, where  $N$  is not restricted to be an integer. It should be noted that the transistor **M1** is not restricted to be a PMOS transistor shown in FIG. 5. Alternatively, the replica transistor may be implemented by an NMOS transistor. FIG. 6 is a diagram illustrating a fourth transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit **104/204** may be implemented using the transistor off-resistance control circuit **600**, and the transistor body-biasing circuit **106** may be implemented using the transistor body-biasing circuit **502**. The major difference between the transistor off-resistance control circuits **500** and **600** is that the transistor **M1** in the transistor off-resistance control circuit **600** is implemented by an NMOS transistor with the control terminal N.sub.1,1 being a gate terminal, the connection terminal N.sub.1,2 being a drain terminal, and the connection terminal N.sub.1,3 being a source terminal, and the operational amplifier **608** included in the transistor off-resistance control circuit **600** has a non-inverting input terminal (+) coupled to the connection terminal N.sub.0,2 of the transistor **M0** and an inverting terminal (-) coupled to the connection terminal (i.e., source terminal) N.sub.1,3 of the transistor **M1** (which is an NMOS transistor).

(29) In the embodiments shown in FIG. 5 and FIG. 6, the bias voltage  $V_B$  at the connection terminal N.sub.1,2 of the transistor **M1** is configured to be higher than the voltage at the connection terminal N.sub.1,3 of the transistor **M1**, and the bias current  $I_B$  is configured to flow from the connection terminal N.sub.1,3 of the transistor **M1** towards the reference voltage (e.g., ground voltage GND). However, this is for illustrative purposes only, and is not meant to be a limitation of the present invention. In practice, the bias current  $I_B$  can be a controllable bias current, and/or the bias voltage  $V_B$  can be a controllable bias voltage.

(30) FIG. 7 is a diagram illustrating a fifth transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit **104/204** may be implemented using the transistor off-resistance control circuit **700**, and the transistor body-biasing circuit **106** may be implemented using the transistor body-biasing circuit **502**. In this embodiment, the transistor off-resistance control circuit **700** has a bias current generator circuit **712** arranged to



provide the connection terminal N.sub.1,3 of the transistor M1 (which may be a PMOS transistor or an NMOS transistor) with the bias current IB, where the bias current generator circuit 712 is coupled between the connection terminal N.sub.1,3 of the transistor M1 (which may be a PMOS transistor or an NMOS transistor) and a reference voltage (e.g., supply voltage VDD), and the bias current IB is configured to flow from the reference voltage (e.g., supply voltage VDD) towards the connection terminal N.sub.1,3 of the transistor M1 (which may be a PMOS transistor or an NMOS transistor). In addition, the connection terminal N.sub.2,2 of the transistor MB included in the bias voltage generator circuit 704 is coupled to another reference voltage (e.g., ground voltage GND), and the voltage source 714 included in the bias voltage generator circuit 704 is arranged to provide the connection terminal N.sub.1,2 of the transistor M1 (which may be a PMOS transistor or an NMOS transistor) with the bias voltage VB that is configured to be lower than the voltage at the connection terminal N.sub.1,3 of the transistor M1.

(31) In this embodiment, the off-resistance Roff,1 of the transistor M1 is defined by VB/IB. Since the control voltage (e.g., gate voltage) at the control terminal N.sub.1,1 of the transistor M1 (which is a replica of the transistor M0, such as N×M0) is mirrored to act as the control voltage (e.g., gate voltage) at the control terminal N.sub.0,1 of the transistor M0, the off-resistance Roff,0 of the transistor M0 is defined by

$$(32) \frac{V_B}{I_B} \times N.$$

Hence, with proper settings of controllable bias voltage VB and controllable bias current IB at the transistor off-resistance control circuit 700, controllable off-resistance Roff,0 of the transistor M0 can be achieved. For example, the off-resistance Roff,0 of the transistor M0 can be reduced to make the noise filter circuit 100/200 meet requirements of an application such as faster settling time, smaller amplifier output voltage, and smaller V\_OUT/V\_IN mismatch.

(33) In above embodiments, the bias voltage VB is created by the voltage source 514/714 coupled between the inverting input terminal (−) of the operational amplifier 506 and the connection terminal N.sub.1,2 of the transistor M1. However, this is for illustrative purposes only, and is not meant to be a limitation of the present invention. In practice, any means capable of generating and applying the bias voltage VB to the connection terminal N.sub.1,2 of the transistor M1 may be employed by the bias voltage generator circuit.

(34) FIG. 8 is a diagram illustrating a sixth transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit 104/204 may be implemented using the transistor off-resistance control circuit 800, and the transistor body-biasing circuit 106 may be implemented using the transistor body-biasing circuit 502. The major difference between the bias voltage generator circuits 504 and 804 is that the bias voltage generator circuit 804 further includes a voltage generator circuit 806 arranged to provide the bias voltage VB, and the inverting input terminal (−) of the operational amplifier 506 is coupled to the connection terminal N.sub.1,2 of the transistor M1 without via any voltage source. In this embodiment, the voltage generator circuit 806 includes a constant current source 808, a variable resistor 810, a transistor 812, and an operational amplifier 814. The variable resistor 810 has one end coupled to the non-inverting input terminal (+) of the operational amplifier 506 and the constant current source 808. Hence, the bias voltage VB established at one end of the variable resistor 810 is applied to the non-inverting input terminal (+) of the operational amplifier 506. Since the resistance value of the variable resistor 810 is adjustable, the bias voltage VB is a controllable bias voltage that can be set to a desired value by tuning the variable resistor 810.

(35) FIG. 9 is a diagram illustrating a seventh transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit 104/204 may be implemented using the transistor off-resistance control circuit 900, and the transistor body-biasing circuit 106 may be implemented using the transistor body-biasing circuit 502. The major difference between the bias voltage generator circuits 904 and 804 is that a voltage generator circuit 906 of the bias voltage generator circuit 904 is arranged to generate the bias voltage VB

through a variable current source **908** and a fixed resistor **910**. The fixed resistor **910** has one end coupled to the non-inverting input terminal (+) of the operational amplifier **506** and the variable current source **908**. Hence, the bias voltage VB established at one end of the fixed resistor **910** is applied to the non-inverting input terminal (+) of the operational amplifier **506**. Since the current provided from the variable current source **908** to the fixed resistor **910** is adjustable, the bias voltage VB is a controllable bias voltage that can be set to a desired value by tuning the variable current source **908**. It should be noted that the present invention has no limitations on the design of the variable current source. In other words, any variable current source can be employed by the bias voltage generator circuit **904**.

(36) The transistor MB included in the bias voltage generator circuit **505/704/804/904** may be implemented by a PMOS transistor or an NMOS transistor, depending upon actual design considerations.

(37) FIG. **10** is a diagram illustrating an eighth transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit **104/204** may be implemented using the transistor off-resistance control circuit **1000**, and the transistor body-biasing circuit **106** may be implemented using the transistor body-biasing circuit **502**. In this embodiment, the transistor MB included in the bias voltage generator circuit **1004** is implemented by an NMOS transistor with the control terminal N.sub.2,1 being a gate terminal, the connection terminal N.sub.2,2 being a drain terminal, and the connection terminal N.sub.2,3 being a source terminal.

(38) FIG. **11** is a diagram illustrating a ninth transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit **104/204** may be implemented using the transistor off-resistance control circuit **1100**, and the transistor body-biasing circuit **106** may be implemented using the transistor body-biasing circuit **502**. In this embodiment, the transistor MB included in the bias voltage generator circuit **1104** is implemented by a PMOS transistor with the control terminal N.sub.2,1 being a gate terminal, the connection terminal N.sub.2,2 being a source terminal, and the connection terminal N.sub.2,3 being a drain terminal. In addition, an operational amplifier **1106** included in the bias voltage generator circuit **1104** has a non-inverting input terminal (+) coupled to the voltage source **514**, and an inverting input terminal (-) coupled to the connection terminal N.sub.0,2 of the transistor **M0** and the inverting input terminal (-) of the operational amplifier **508**.

(39) With regard to the transistor body-biasing circuit **502** shown in FIGS. **5-11**, it includes an operational amplifier **510** configured to act as a unity-gain buffer (also called a unity-gain amplifier), where the non-inverting input terminal (+) of the operational amplifier **510** is coupled to the connection terminal N.sub.0,2 of the transistor **M0**, and the output terminal of the of the operational amplifier **510** is coupled to the inverting input terminal (-) of the operational amplifier **510**, the body terminal N.sub.0,4 of the transistor **M0**, and the body terminal N.sub.1,4 of the transistor **M1**. Due to inherent characteristics of the unity-gain buffer, the operational amplifier **510** drives the bulk/body/substrate of both transistors **M0** and **M1** by the same voltage (e.g.,  $V_{IN}$ ) at the connection terminal N.sub.0,2 of the transistor **M0**. However, this is for illustrative purposes only, and is not meant to be a limitation of the present invention. In practice, any means capable of making the bulk/body/substrate of both transistors **M0** and **M1** biased at the same voltage or similar voltages can be employed by the noise filter circuit **100/200**.

(40) FIG. **12** is a diagram illustrating a tenth transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit **104/204** may be implemented using the transistor off-resistance control circuit **1200**, and the transistor body-biasing circuit **106** may be implemented using the transistor body-biasing circuit **1202**. The transistor body-biasing circuit **1202** includes an operational amplifier **1210** configured to act as a unity-gain buffer (also called a unity-gain amplifier), where the non-inverting input terminal (+) of the operational amplifier **1210** is coupled to the connection terminal N.sub.0,3 of the transistor **M0**, and the output

terminal of the of the operational amplifier **1210** is coupled to the inverting input terminal (–) of the operational amplifier **1210**, the body terminal N.sub.0,4 of the transistor **M0**, and the body terminal N.sub.1,4 of the transistor **M1**. Due to inherent characteristics of the unity-gain buffer, the operational amplifier **1210** drives the bulk/body/substrate of both transistors **M0** and **M1** by the same voltage (e.g., V\_OUT) at the connection terminal N.sub.0,3 of the transistor **M0**.

(41) FIG. **13** is a diagram illustrating an eleventh transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit **104/204** may be implemented using the transistor off-resistance control circuit **1300**. The noise filter circuit **100/200** may be modified to omit the transistor body-biasing circuit **106**. Since there is no transistor body-biasing circuit **106**, a body terminal of a transistor can be tied to a source terminal of the same transistor. For example, the transistor **M0** may be a PMOS transistor with the body terminal N.sub.0,4 coupled to the connection terminal (i.e., source terminal) N.sub.0,2 at which the input voltage V\_IN is received by the RC based filter **102**; and the transistor **M1** may be an NMOS transistor with the body terminal N.sub.1,4 coupled to the connection terminal (i.e., source terminal) N.sub.1,3.

(42) FIG. **14** is a diagram illustrating a twelfth transistor off-resistance control circuit according to an embodiment of the present invention. The transistor off-resistance control circuit **104/204** may be implemented using the transistor off-resistance control circuit **1400**. The noise filter circuit **100/200** may be modified to omit the transistor body-biasing circuit **106**. Since there is no transistor body-biasing circuit **106**, a body terminal of a transistor can be tied to a source terminal of the same transistor. For example, the transistor **M0** may be an NMOS transistor with the body terminal N.sub.0,4 coupled to the connection terminal (i.e., source terminal) N.sub.0,3 at which the output voltage V\_OUT is output from the RC based filter **102**; and the transistor **M1** may be an NMOS transistor with the body terminal N.sub.1,4 coupled to the connection terminal (i.e., source terminal) N.sub.1,3.

(43) It should be noted that the scope of the present invention is not limited by the aforementioned embodiments. Any noise filter circuit design using one or more features supported by embodiments mentioned above falls within the scope of the present invention. For example, a noise filter circuit design using features directed to a replica transistor **M1** not restricted to an NMOS transistor or a PMOS transistor, a controllable bias current IB, a controllable bias voltage VB, a transistor MB not restricted to an NMOS transistor or a PMOS transistor, and/or a transistor **M0** and a replica transistor **M1** biased at the same voltage or similar voltages falls within the scope of the present invention.

(44) Those skilled in the art will readily observe that numerous modifications and alterations of the device and method may be made while retaining the teachings of the invention. Accordingly, the above disclosure should be construed as limited only by the metes and bounds of the appended claims.

## Claims

1. A noise filter circuit comprising: a filter, comprising: a first transistor, arranged to have off-resistance when turned off or operated under sub-threshold region, wherein the first transistor comprises: a control terminal, arranged to receive a first control voltage, wherein the control terminal is not directly tied to a reference voltage; a first connection terminal; and a second connection terminal; and a charge storage component, having one terminal coupled to the second connection terminal of the first transistor; and a transistor off-resistance control circuit, coupled to the first transistor and arranged to set the first control voltage for controlling the off-resistance of the first transistor.
2. The noise filter circuit of claim 1, wherein the filter is a low-pass filter, the first connection terminal is arranged to receive an input voltage of the low-pass filter, and the second connection

terminal is arranged to output an output voltage of the low-pass filter.

3. The noise filter circuit of claim 1, wherein the first transistor is located at a forward path of the noise filter circuit, the noise filter circuit further comprises a second transistor located at a feedback path of the noise filter circuit and arranged to have off-resistance when turned off or operated under sub-threshold region, the second transistor has a control terminal arranged to receive a second control voltage, the control terminal of the second transistor is not directly tied to a reference voltage, and the transistor off-resistance control circuit is further coupled to the second transistor and arranged to set the second control voltage for controlling the off-resistance of the second transistor.

4. The noise filter circuit of claim 1, wherein the transistor off-resistance control circuit comprises: a second transistor, being a replica of the first transistor and comprising: a control terminal, arranged to generate a second control voltage; a first connection terminal; and a second connection terminal; wherein the second control voltage at the control terminal of the second transistor is mirrored to act as the first control voltage of the first transistor.

5. The noise filter circuit of claim 4, wherein the control terminal of the second transistor is directly connected to the control terminal of the first transistor.

6. The noise filter circuit of claim 4, wherein the transistor off-resistance control circuit further comprises: a buffer circuit, having an input terminal coupled the control terminal of the second transistor and an output terminal coupled to the control terminal of the first transistor.

7. The noise filter circuit of claim 4, wherein the transistor off-resistance control circuit further comprises: a bias voltage generator circuit, arranged to provide the first connection terminal of the second transistor with a bias voltage; and a bias current generator circuit, arranged to provide the second connection terminal of the second transistor with a bias current.

8. The noise filter circuit of claim 7, wherein the bias voltage at the first connection terminal of the second transistor is configured to be higher than a voltage at the second connection terminal of the second transistor, and the bias current is configured to flow from the second connection terminal of the second transistor towards a reference voltage.

9. The noise filter circuit of claim 7, wherein the bias voltage at the first connection terminal of the second transistor is configured to be lower than a voltage at the second connection terminal of the second transistor, and the bias current is configured to flow from a reference voltage towards the second connection terminal of the second transistor.

10. The noise filter circuit of claim 7, wherein the bias voltage generator circuit comprises: an operational amplifier, comprising: a first input terminal, arranged to receive the input voltage of the noise filter circuit; a second input terminal; and an output terminal; a third transistor, comprising: a control terminal, coupled to the output terminal of the operational amplifier; a first connection terminal, arranged to receive a reference voltage; and a second connection terminal, coupled to the first connection terminal of the second transistor; and a voltage source, coupled between the second input terminal of the operational amplifier and the first connection terminal of the second transistor, wherein the voltage source is arranged to provide the bias voltage.

11. The noise filter circuit of claim 7, wherein the bias voltage generator circuit comprises: a voltage generator circuit, arranged to provide the bias voltage; and an operational amplifier, comprising: a first input terminal, coupled to the voltage generator circuit and arranged to receive the bias voltage; a second input terminal, coupled to the first connection terminal of the second transistor; and an output terminal; a third transistor, comprising: a control terminal, coupled to the output terminal of the operational amplifier; a first connection terminal, arranged to receive a reference voltage; and a second connection terminal, coupled to the first connection terminal of the second transistor.

12. The noise filter circuit of claim 11, wherein the voltage generator circuit comprises: a variable resistor, having one end coupled to the first input terminal of the operational amplifier; and a constant current source, coupled to said one end of the variable resistor.

13. The noise filter circuit of claim 11, wherein the voltage generator circuit comprises: a fixed resistor, having one end coupled to the first input terminal of the operational amplifier; and a variable current source, coupled to said one end of the fixed resistor.
14. The noise filter circuit of claim 4, wherein the transistor off-resistance control circuit further comprises: an operational amplifier, comprising: a first input terminal, coupled to the first connection terminal of the first transistor; a second input terminal, coupled to the second connection terminal of the second transistor; and an output terminal, coupled to the control terminal of the second transistor.
15. The noise filter circuit of claim 4, wherein the transistor off-resistance control circuit further comprises: a transistor body-biasing circuit, arranged to generate and apply a same body voltage to both of the first transistor and the second transistor.
16. The noise filter circuit of claim 15, wherein the transistor body-biasing circuit comprises: an operational amplifier, comprising: a first input terminal, coupled to the first connection terminal of the first transistor; a second input terminal; and an output terminal, coupled to the second input terminal of the operational amplifier, a body terminal of the first transistor, and a body terminal of the second transistor.
17. The noise filter circuit of claim 15, wherein the transistor body-biasing circuit comprises: an operational amplifier, comprising: a first input terminal, coupled to the second connection terminal of the first transistor; a second input terminal; and an output terminal, coupled to the second input terminal of the operational amplifier, a body terminal of the first transistor, and a body terminal of the second transistor.
18. The noise filter circuit of claim 4, wherein a body terminal of the first transistor is tied to the first connection terminal of the first transistor, and a body terminal of the second transistor is tied to the second connection terminal of the second transistor.
19. The noise filter circuit of claim 4, wherein a body terminal of the first transistor is tied to the second connection terminal of the first transistor, and a body terminal of the second transistor is tied to the second connection terminal of the second transistor.
20. A noise filtering method comprising: setting a control voltage at a control terminal of a transistor for controlling off-resistance of the transistor, wherein the control terminal of the transistor is not directly tied to a reference voltage; and performing a filtering operation upon an input voltage to generate an output voltage, wherein the filtering operation is based on the transistor and a charge storage component.
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