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(54) **CIRCUITS WITH DYNAMIC BIASING**

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(51) **Int. Cl.^{7}** **H03B 1/00**
(52) **U.S. Cl.** **327/552**
(58) **Field of Search** 327/551, 552, 327/557, 558, 559

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(57) **ABSTRACT**

Techniques are provided for the implementation of dynamically biased circuits. In these circuits, bias currents are varied according to signal amplitude. Benefits include reduced power dissipation, reduced noise, and increased dynamic range. The techniques can be employed in various types of circuits such as, for example, amplifiers, log-domain circuits, and filters.

4 Claims, 17 Drawing Sheets
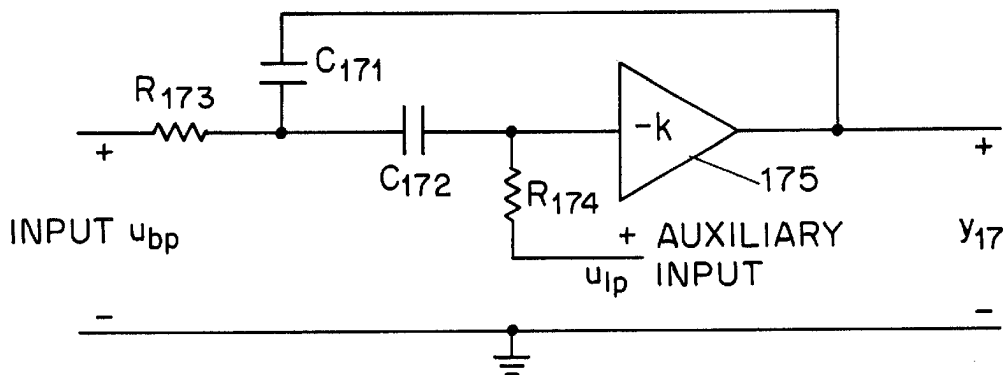
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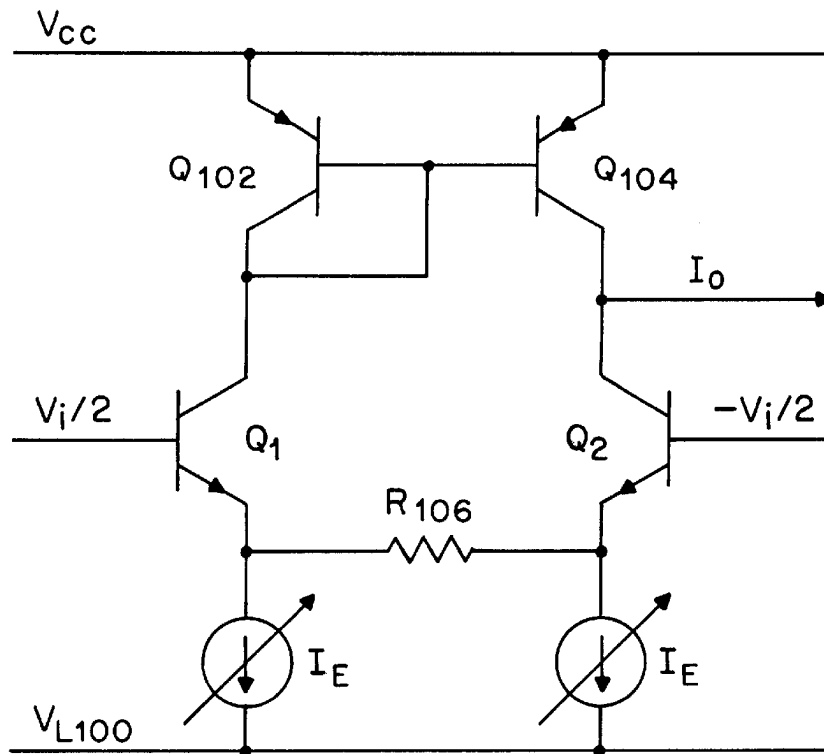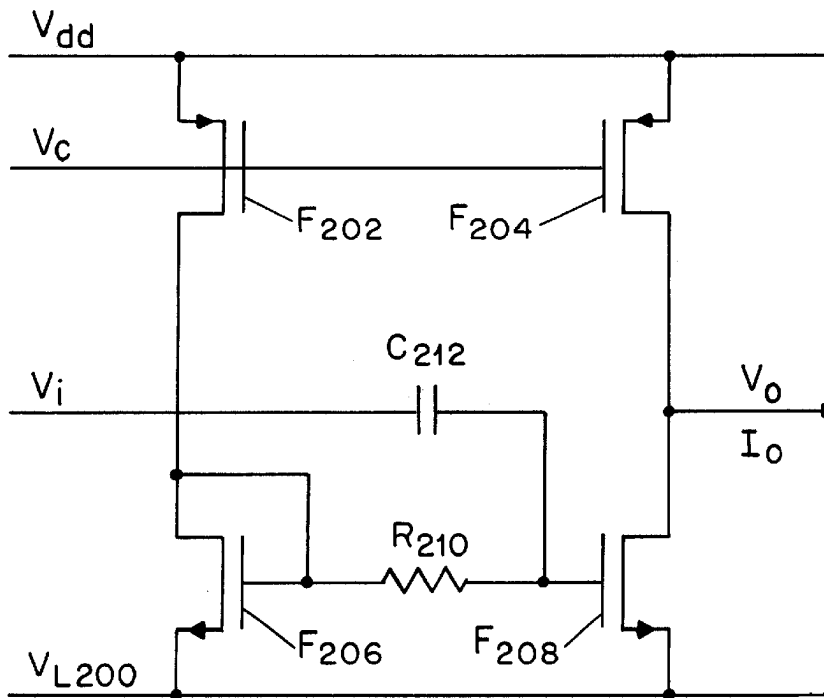
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V_{cc}

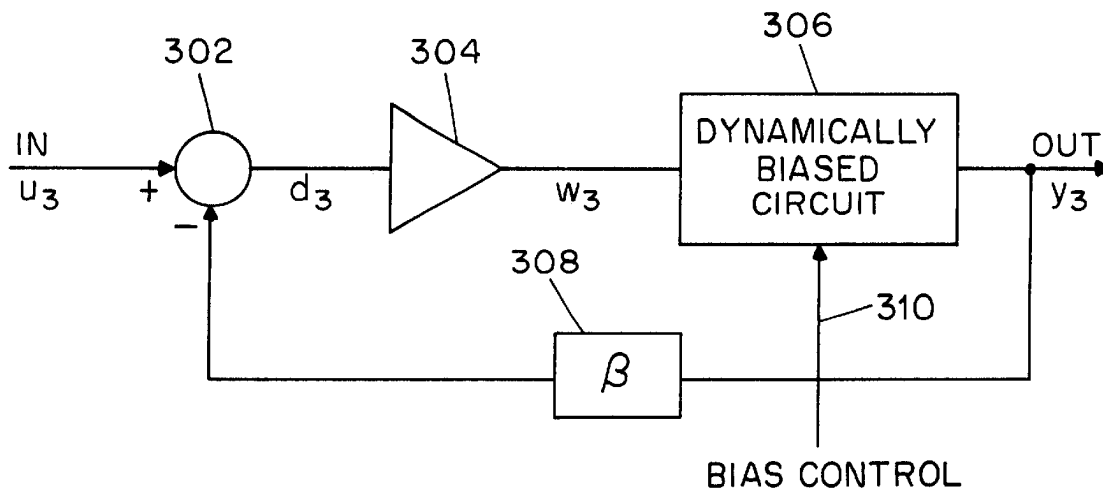Q_{102} Q_{104}

I_o

$V_i/2$ Q_1 Q_2 $-V_i/2$

R_{106}

I_E I_E

V_{L100}

FIG. 1

V_{dd}

V_c

F_{202} F_{204}

C_{212}

V_i V_o

I_o

R_{210}

F_{206} F_{208}

V_{L200}

FIG. 2

IN
u_3 → 302 → + ⊖ − d_3 → 304 ▷ w_3 → 306 ┌─────────────┐ DYNAMICALLY BIASED CIRCUIT └─────────────┘ OUT
y_3 →

308 │ β │

310

BIAS CONTROL

FIG. 3

V_{out} vs V_{in}

$V_{in}(t)$

FIG. 4

502

506

MAIN INPUT
(BP OR HP)

508

OUT

504 — LP IN

BIAS

FIG. 5

614

610

604

602

606

OUT
(BP OR HP)

612

(LP)

608 — (LP OUT)

FIG. 6

704

708

IN

MAIN
CIRCUIT

OUT

706

• • •

CONTROLS

AUXILIARY
CIRCUIT

702

FIG. 7

FIG. 8a

FIG. 8b

5/17

$I_{bias}(t)$

908   902

$+i_{in}$

H(s)

$i_{out\,p}$

DIFFERENTIAL
OUTPUT

$-i_{in}$

H(s)

$i_{out\,n}$

$I_{bias}(t)$

904

FIG. 9a

$I_{bias}(t)$ 902

i_{in}

H(s)

906

i_{out}

$+$

$-$

$I_{bias}(t)$

H(s)

904

FIG. 9b

1106

u

$u-y$

A EXP( )

u_f

$\dfrac{1}{1+s/\omega_p}$

y

$+$

$-$

1102   1104

FIG. 11

FIG. 10a

FIG. 10b

FIG. 10c

FIG. 10d

FIG. 10e

FIG. 10f

FIG. 12

FIG. 13

FIG. 15a

FIG. 15b

FIG. 14

FIG. 16

FIG. 17a

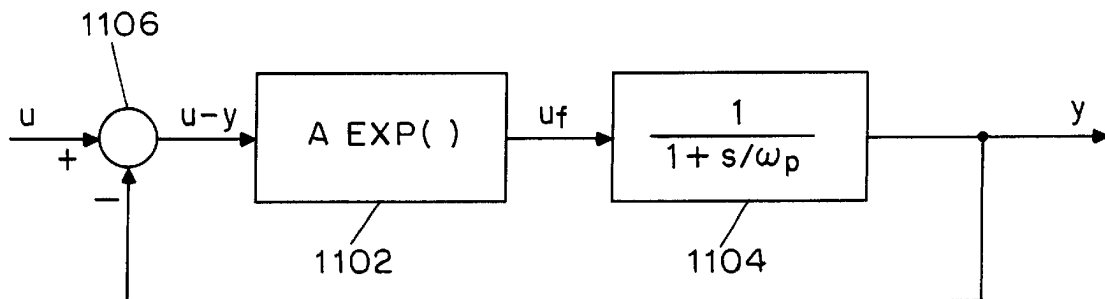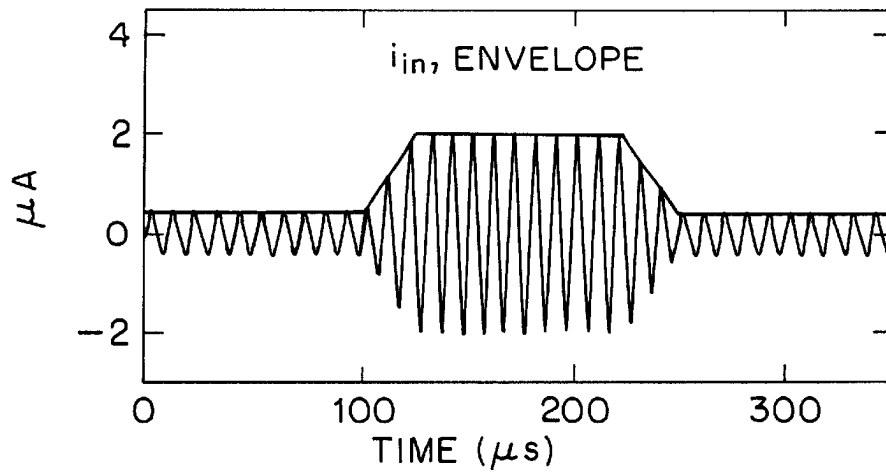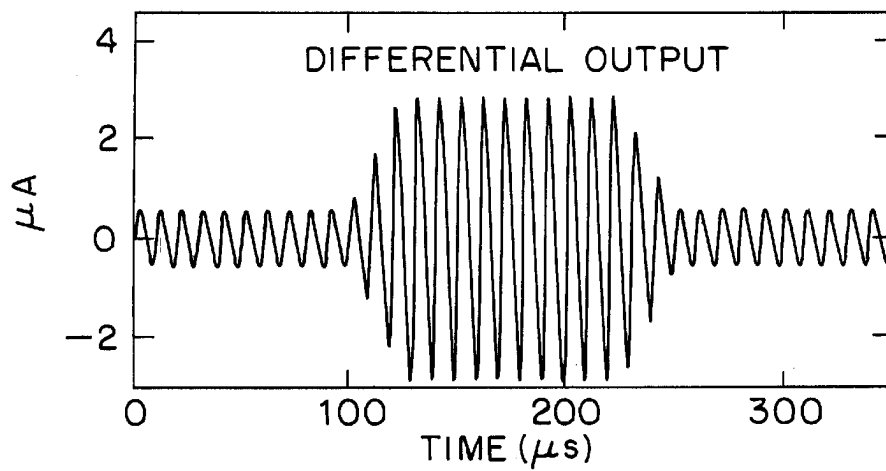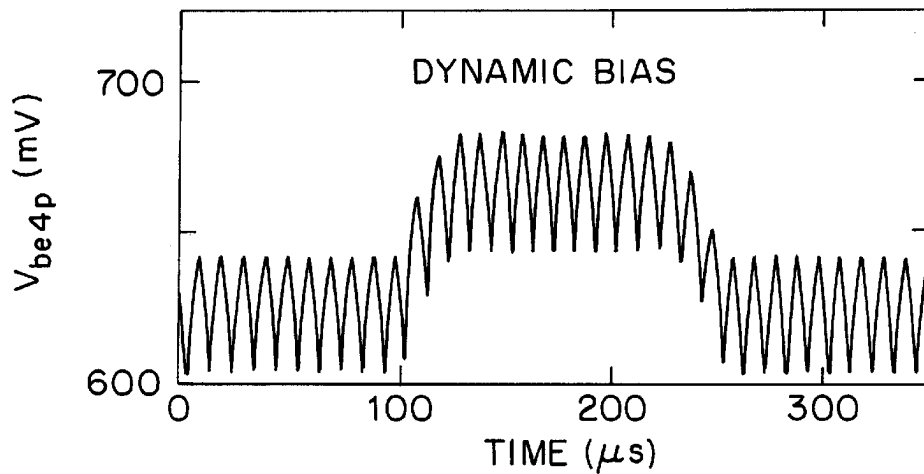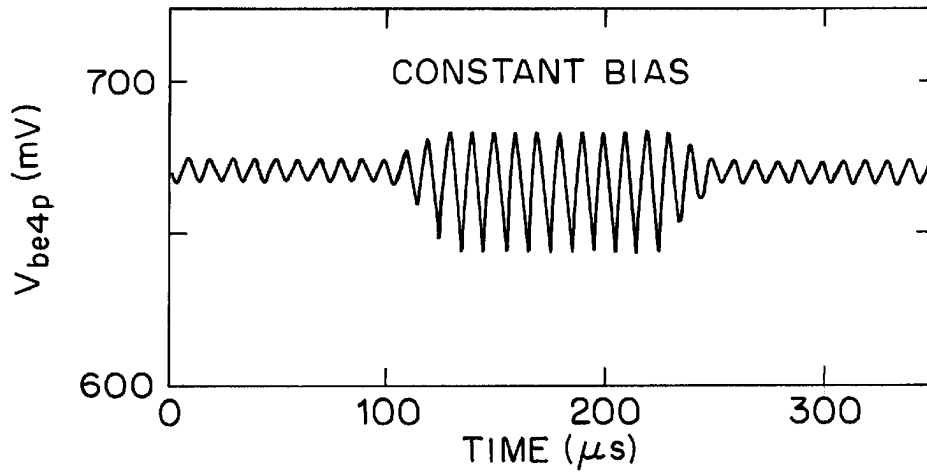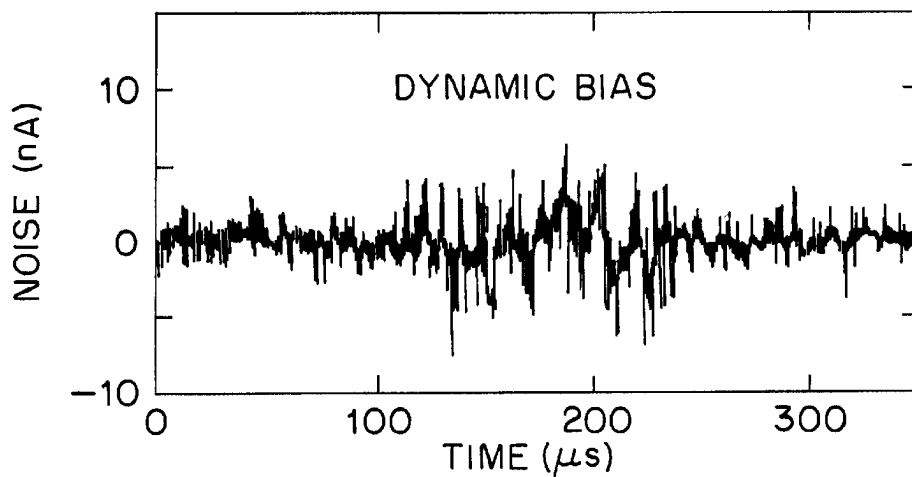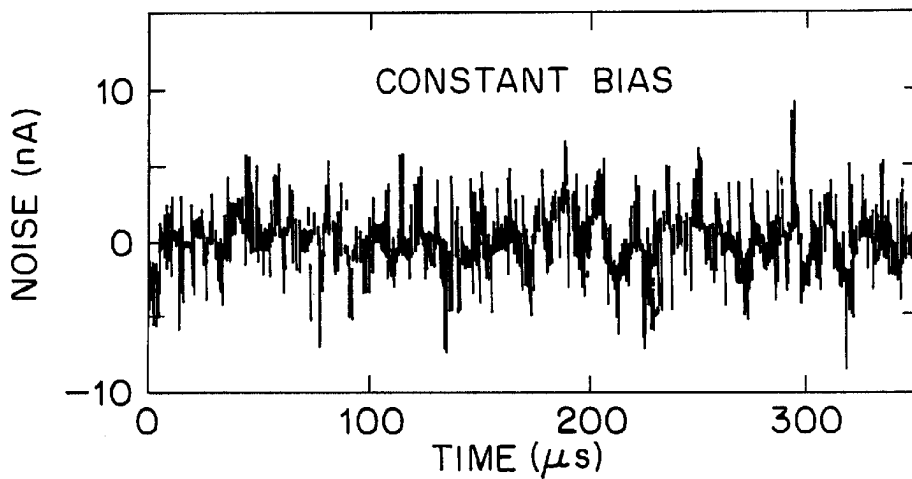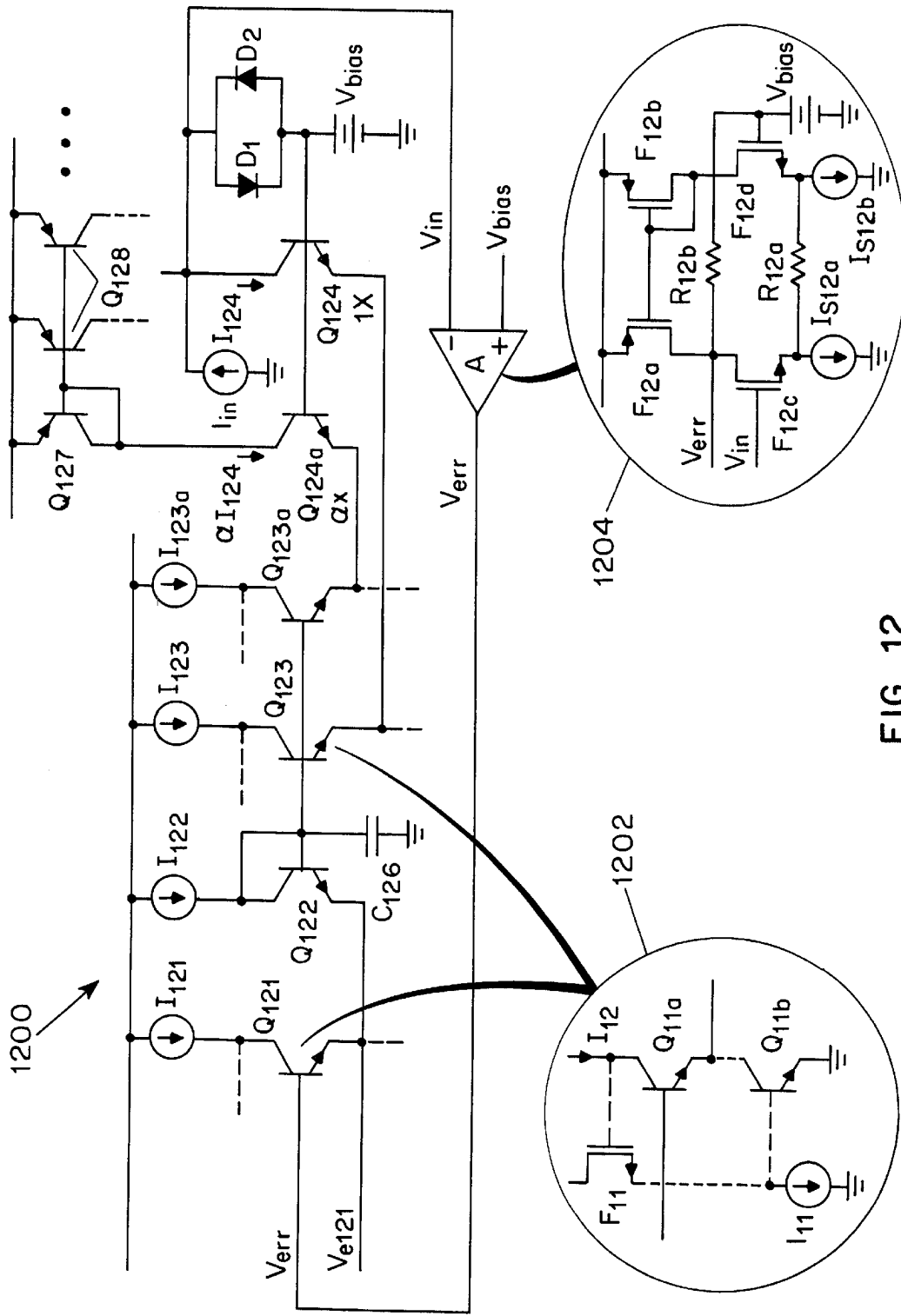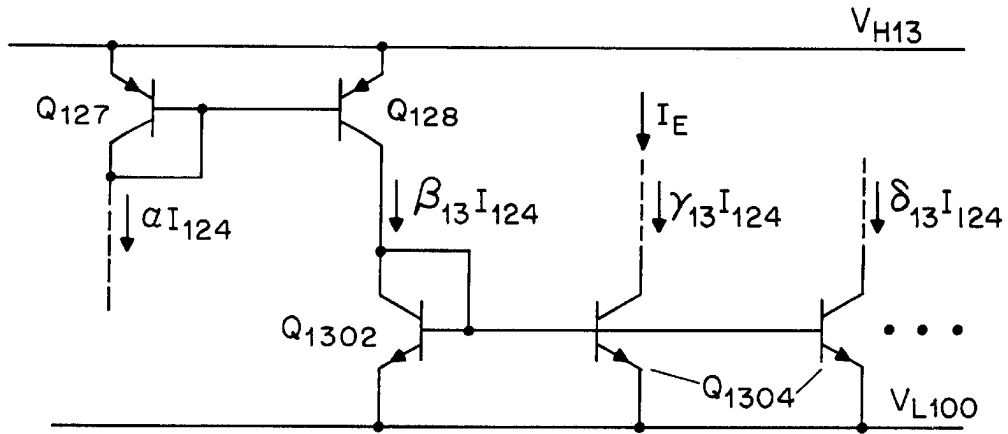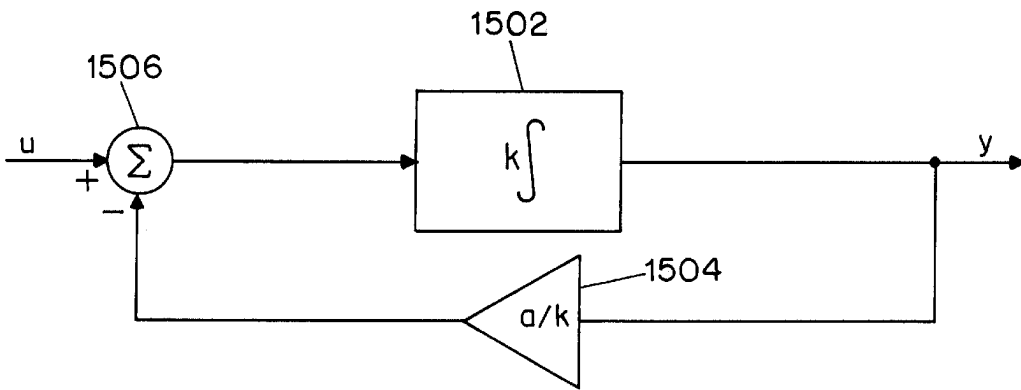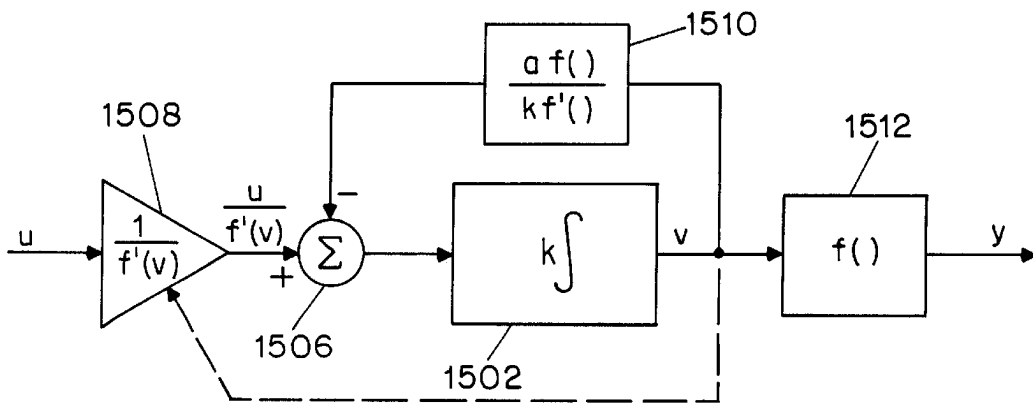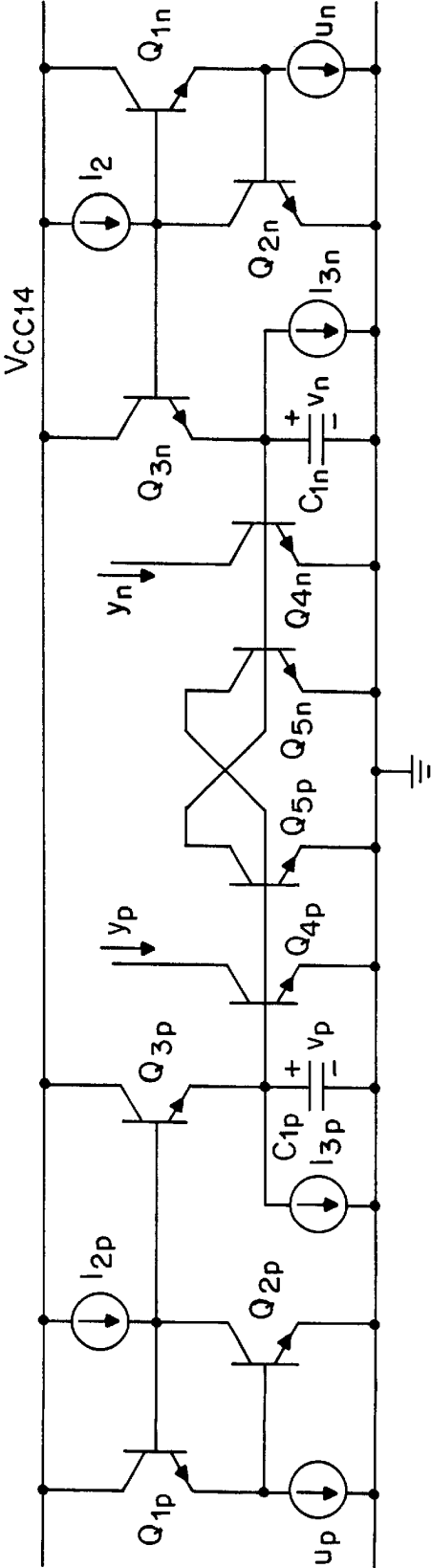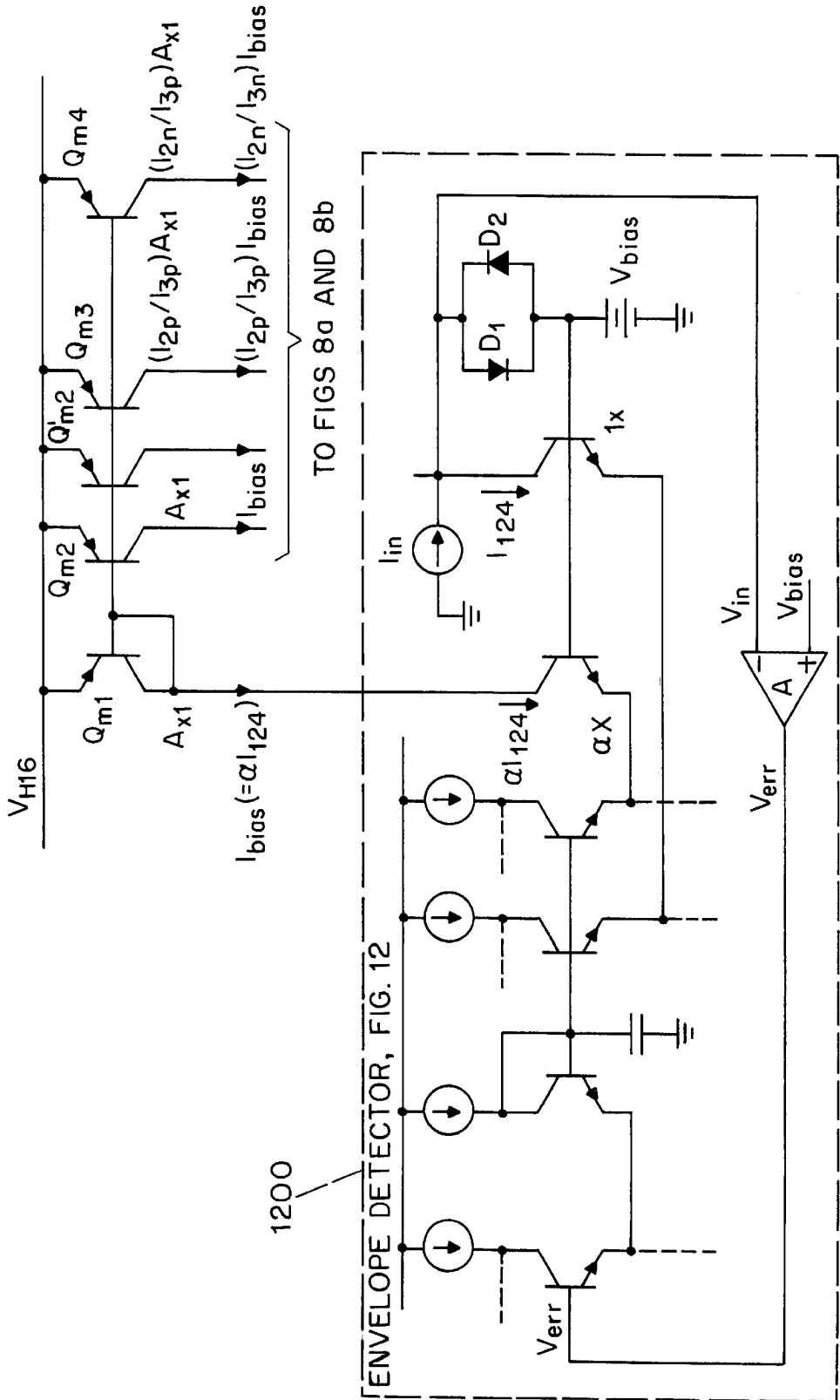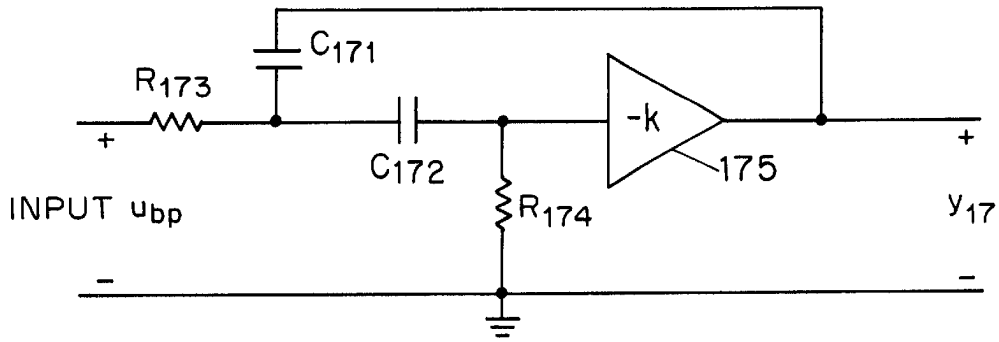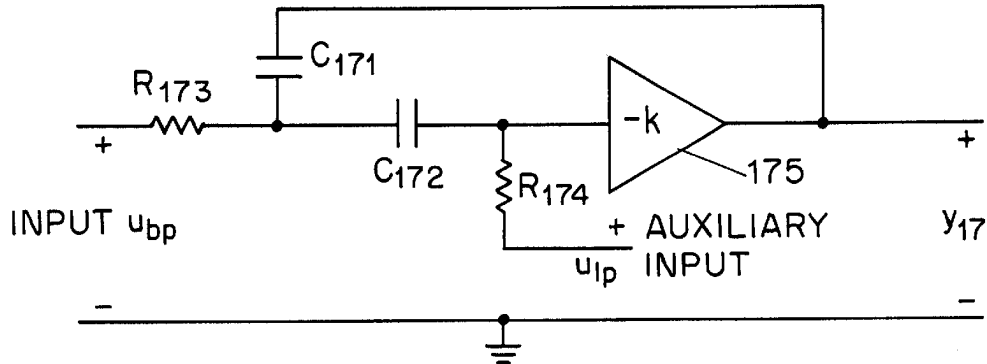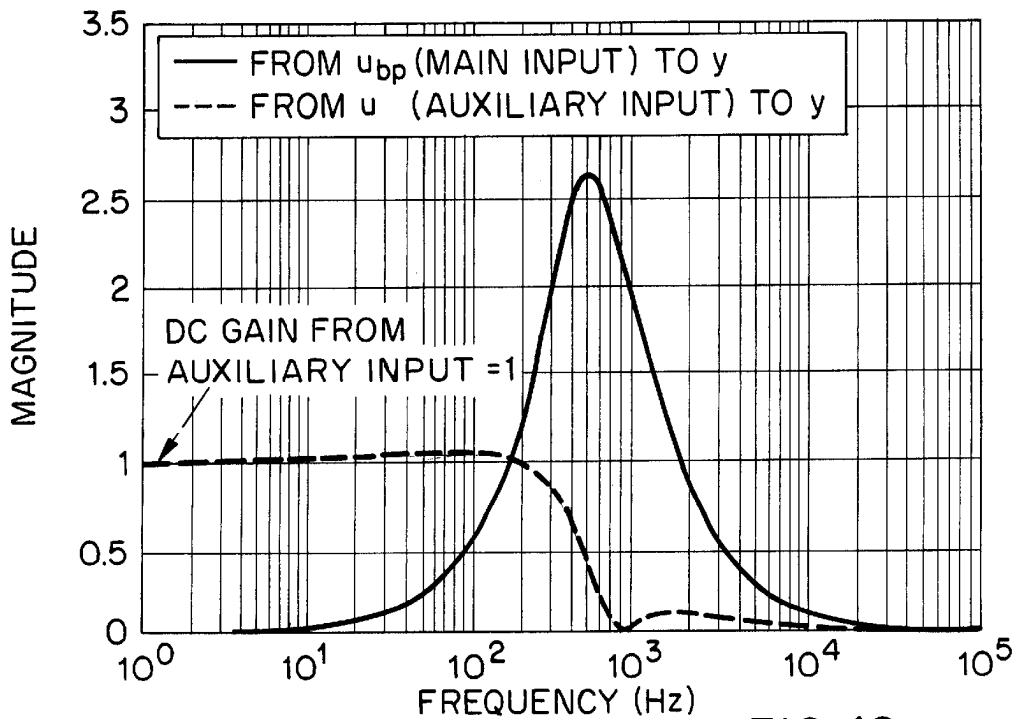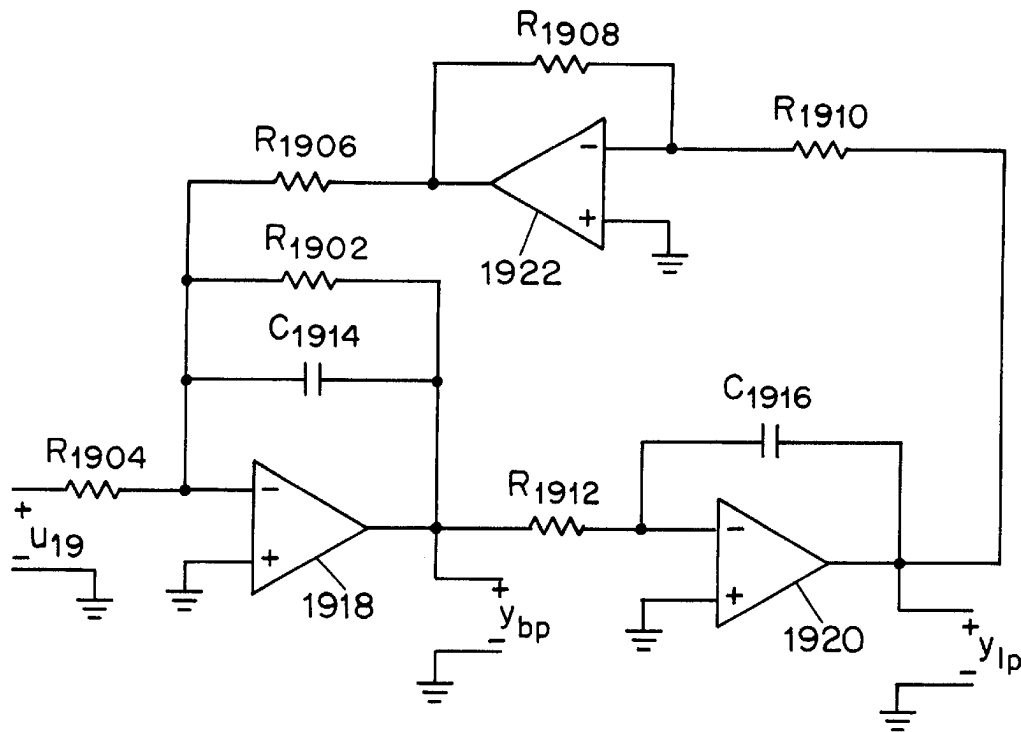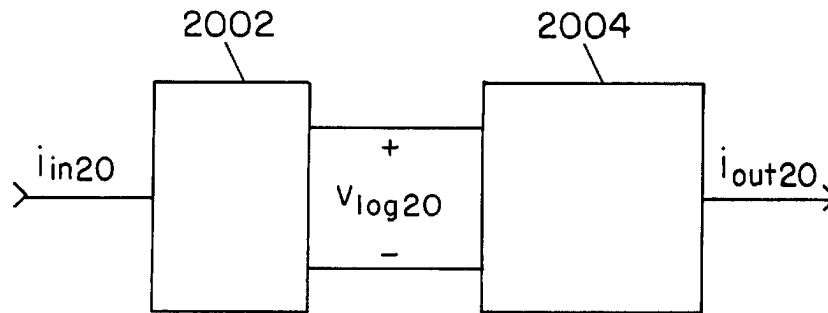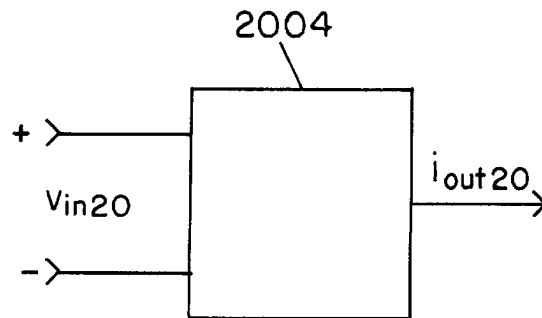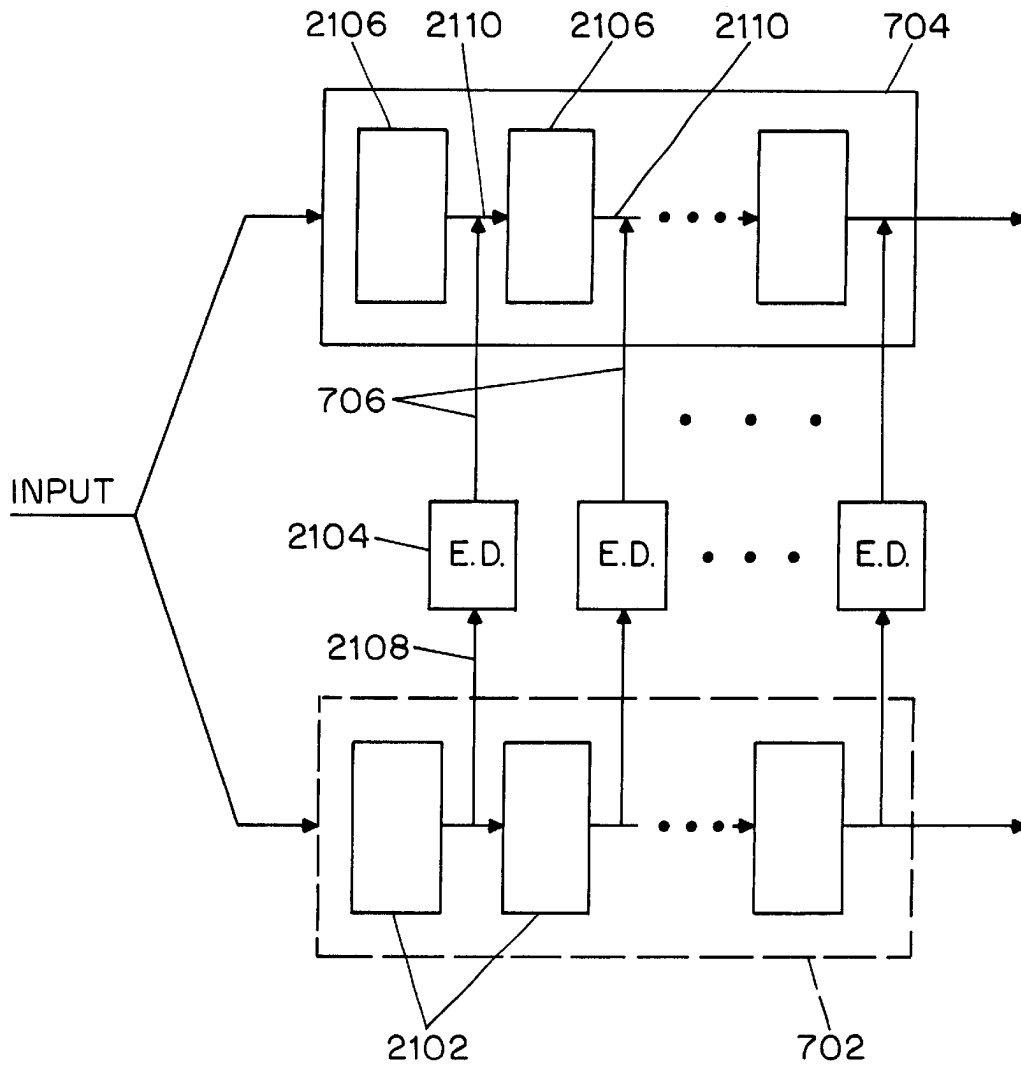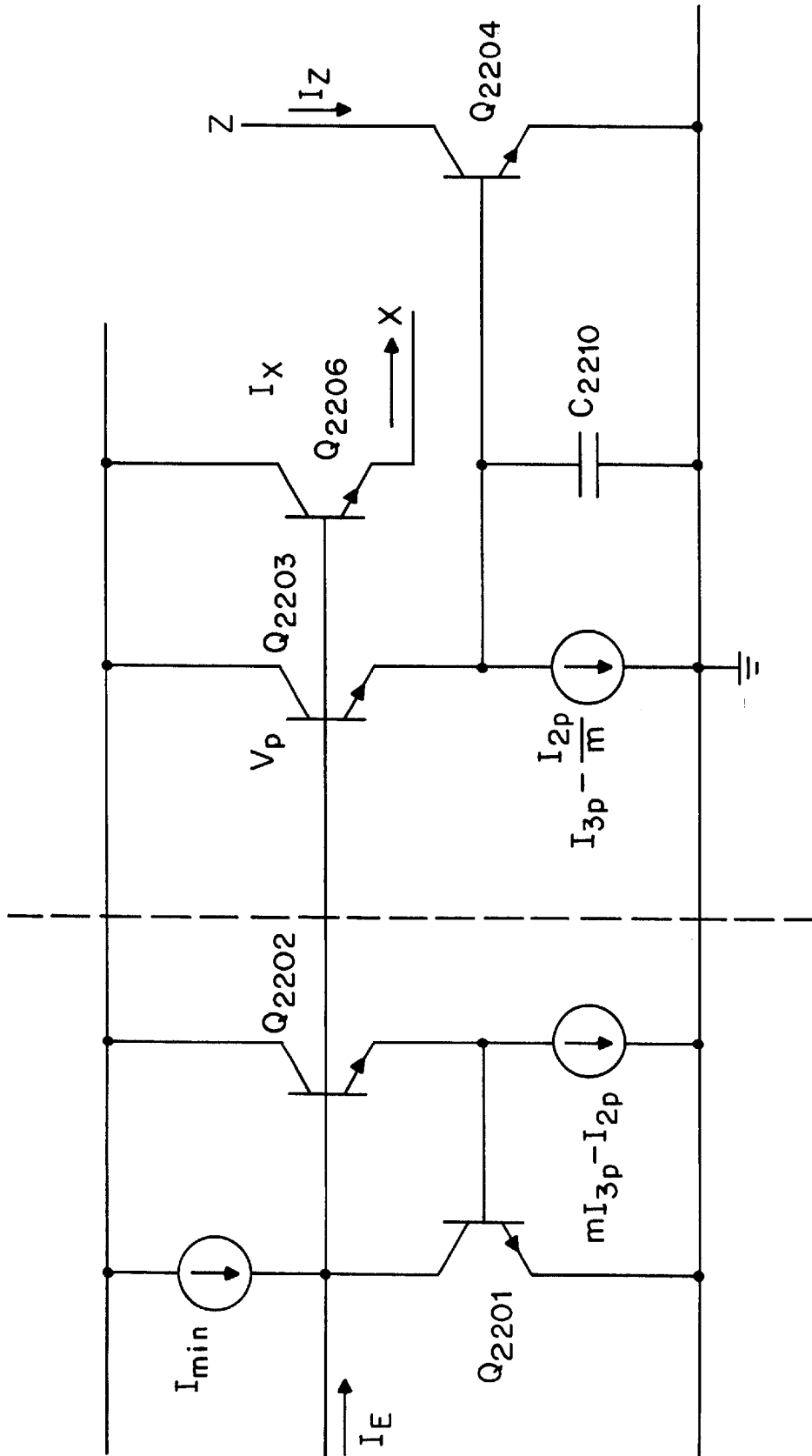FIG. 17b

FIG. 18

FIG. 19

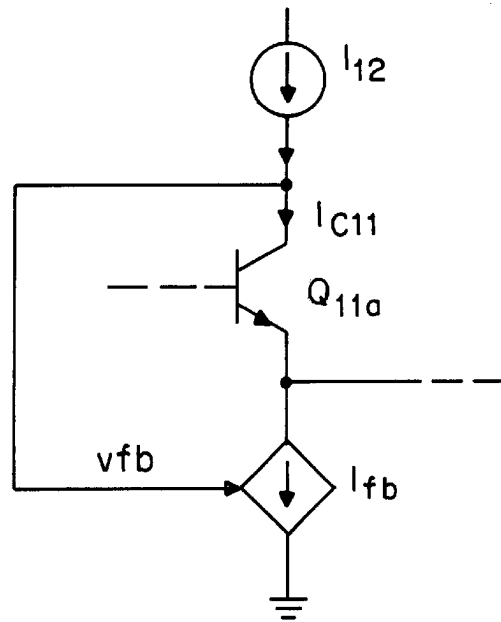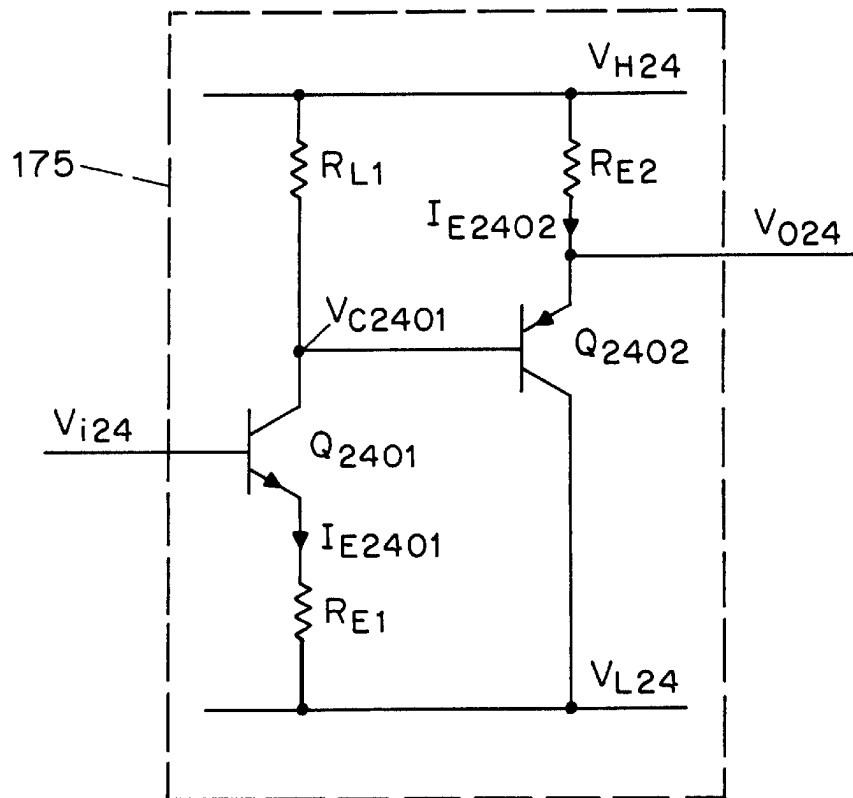FIG. 20a

FIG. 20b

FIG. 21
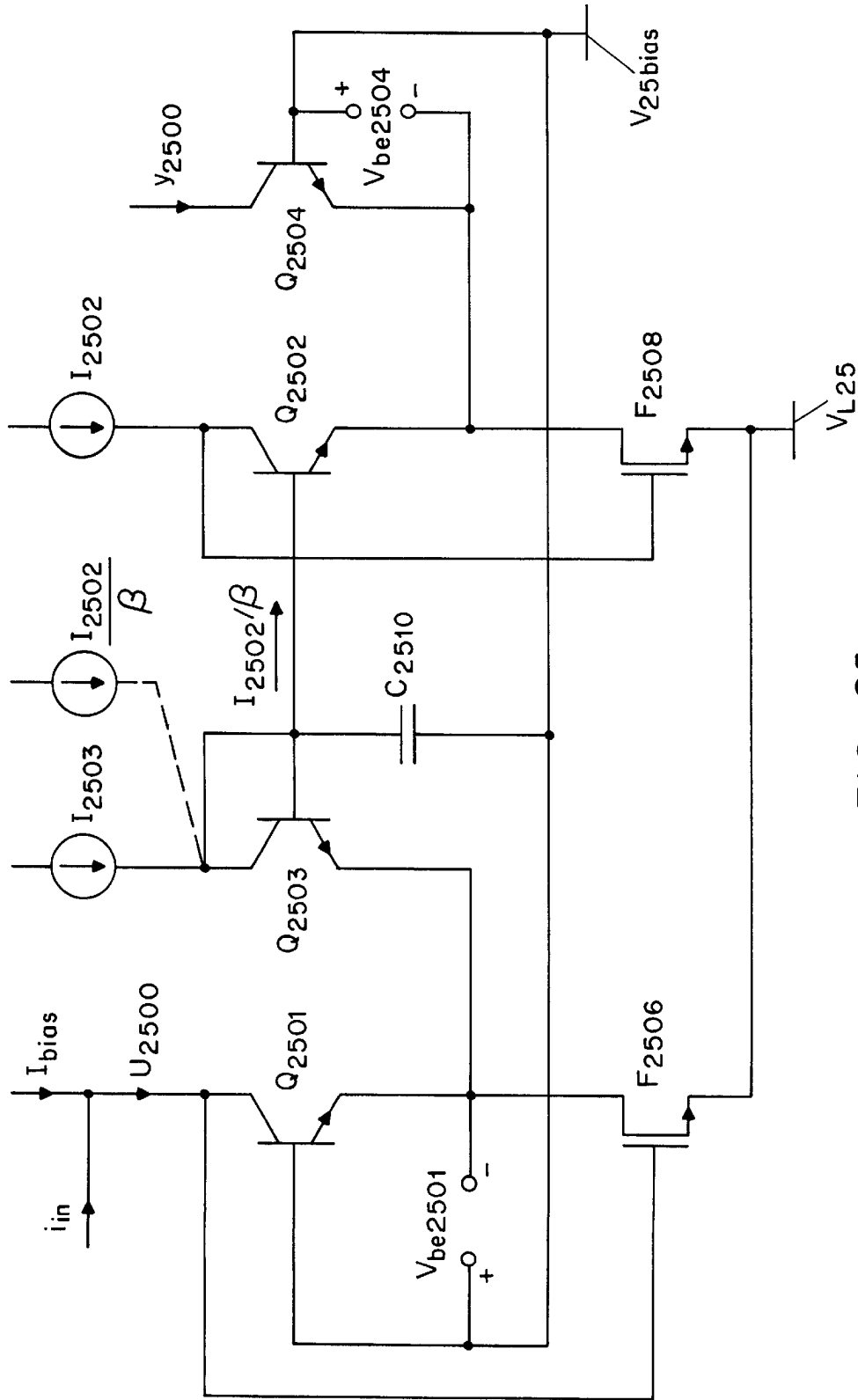
FIG. 22

FIG. 23

FIG. 24

FIG. 25

CIRCUITS WITH DYNAMIC BIASING

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. Provisional Patent Application entitled "Circuits with Dynamic Biasing," Ser. No. 60/180,311, which was filed on Feb. 4, 2000.

BACKGROUND OF THE INVENTION

In order to conserve energy in electronic circuits, particularly in battery-operated electronics, it is preferable to use bias currents which are no larger than necessary. Therefore, because the minimum required bias current tends to depend on signal amplitude, it is often desirable to use actual bias currents which are dependent on the amplitude of the signal. An additional advantage of amplitude-dependent biasing is that, if the bias current is only as large as needed, it will produce the least possible amount of noise (e.g., shot noise). These advantages have been discussed in the electronics literature with respect to at least one specific log-domain circuit. D. R. Frey and Y. P. Tsividis, "Syllabically Companding Log Domain Filter Using Dynamic Biasing," Electronics Letters, vol. 33, no. 5, Aug. 28, 1997. Amplitude-dependent biasing can used in other circuits, e.g., amplifiers. However, one potential problem is that the bias can, in some cases, interact with the signal. Accordingly, there is a need for circuits in which the bias control and the signal properties are "orthogonal"—i.e., do not interact with each other.

SUMMARY OF THE INVENTION

It is therefore an object of the invention to provide a circuit which can accommodate signals of various amplitudes in an energy-efficient manner.

It is a further object of the invention to provide a circuit which can accommodate signals of various amplitudes while maintaining a high signal-to-noise ratio.

It is yet another object of the invention to provide a circuit which can accommodate signals of various amplitudes while avoiding excessive interaction between the bias control and the signal.

These and other objects are accomplished by a circuit having a bias which can be adjusted according to a signal which is received, generated, or transmitted by the circuit.

In accordance with one aspect of the invention, a signal is processed using an apparatus comprising: (1) a selected one of a class-AB circuit and a class-B circuit, the selected one having at least one input and at least one bias, the at least one input being adapted to receive at least one input signal, and the selected one being configured to process the at least one input signal to thereby generate at least one output signal related to the at least one input signal by an input-output characteristic having a crossover region which exhibits distortion; and (2) an amplitude detector configured to perform the operations of: (a) receiving the at least one input signal; (b) detecting at least one amplitude of the at least one input signal, and (c) dynamically adjusting the at least one bias in accordance with the at least one amplitude, wherein the at least one bias controls a level of the at least one output signal such that the at least one output signal avoids the crossover region.

In accordance with another aspect of the invention, a signal is processed using a filter having at least one input and at least one bias, wherein the at least one input comprises: (1) a first input for receiving a first input signal; and (2) a second input for receiving a second input signal, wherein the

filter is configured to perform the steps of: (a) applying a first filtering operation to the first input signal, thereby generating a first output signal which is communicated to at least one output of the filter, the first filtering operation having a first frequency characteristic in which low frequencies are suppressed, and (b) applying a second filtering operation to the second input signal, the second input signal controlling the at least one bias, the second filtering operation having a second frequency characteristic in which low frequencies are passed, and the second input signal being adjusted in accordance with an amplitude of the first input signal.

In accordance with an additional aspect of the invention, a signal is processed using a filter having at least one input and first and second biases, wherein the at least one input comprises first and second inputs, the first input being adapted to receive a first input signal and a first bias signal related to an amplitude of at least one of the first and second input signals, the first bias signal being for controlling the first bias, the second input being adapted to receive a second input signal and a second bias signal, the second bias signal being for controlling the second bias, the second bias signal being approximately equal to the first bias signal, and the filter being configured to filter a difference of first and second input signals, thereby generating a filter output signal.

In accordance with another aspect of the invention, a signal is processed using a combined filter comprising: (1) a first filter having a first filter configuration, a first bias input for receiving a first bias, a first input for receiving a first input signal, and a first output for providing a first output signal; (2) a second filter having a second filter configuration, a second bias input for receiving a second bias, a second input for receiving a second input signal, and a second output for providing a second output signal, the second filter configuration matching the first filter configuration, the first bias and the second bias being adjusted in accordance with at least one amplitude of at least one of the first input signal and the second input signal, and the first bias and the second bias being adjusted to be approximately equal; and (3) a combined filter output configured to provide a combined output signal comprising a difference of the first output signal and the second output signal.

In accordance with yet another aspect of the invention, a signal is processed using an apparatus comprising: (1) a first transistor, comprising a first signal-receiving terminal, a first current-carrying terminal adapted to be connected to a voltage source, and a second current-carrying terminal connected to the first signal-receiving terminal; (2) a second transistor, comprising: a second signal-receiving terminal connected to the first signal-receiving terminal, a third current-carrying terminal adapted to be connected to the voltage source, and a fourth current-carrying terminal; (3) a first adjustable current source in communication with the second current-carrying terminal and allowing a first bias current to flow through the second current-carrying terminal; (4) a second adjustable current source in communication with the fourth current-carrying terminal and allowing a second bias current to flow through the fourth current-carrying terminal, the second bias current being approximately equal to the first bias current, and the first and second adjustable current sources being adjusted in accordance with an amplitude of a first input signal coupled into at least one of the second current-carrying terminal and the fourth current-carrying terminal; and (5) an output connected to the fourth current-carrying terminal.

In accordance with an additional aspect of the invention, a signal is processed using an apparatus comprising: (1) a

3

dynamically biased signal-processing circuit having an input and an output; and (2) a feedback path providing a feedback signal from the output to the input.

In accordance with a further aspect of the invention, a signal size is detected by a detector comprising: (1) a differencing block configured to perform the operations of: (a) receiving a first input signal, (b) receiving a second input signal, and (c) generating a difference signal comprising a difference of the first and second input signals; (2) an exponentiator configured to exponentiate a signal comprising the difference signal, thereby generating an exponentiated signal, wherein an output signal of the detector comprises the exponentiated signal; and (3) a filter configured to perform low-pass filtering of a signal comprising the difference signal, thereby generating a filtered signal, wherein the output signal further comprises the filtered signal, and wherein the second input signal comprises the output signal.

In accordance with yet another aspect of the invention, a signal size is detected by a detector comprising: (1) first, second, third, fourth, and fifth nodes, wherein an input signal is received by the first node; (2) a first transistor, comprising: (a) a first signal-receiving terminal connected to the second node, (b) a first current-carrying terminal connected to the third node, and (c) a second current-carrying terminal adapted to receive a first bias current; (3) a second transistor, comprising: (a) a second signal-receiving terminal connected to the fourth node, (b) a third current-carrying terminal connected to the third node, and (c) a fourth current-carrying terminal adapted to receive a second bias current, the fourth current-carrying terminal being connected to the fourth node; (4) a high-frequency shunt connected between the fourth node and a first voltage node, the first voltage node being adapted to be connected to a first voltage source; (5) a third transistor, comprising: (a) a third signal-receiving terminal connected to the fourth node, (b) a fifth current-carrying terminal connected to the fifth node, and (c) a sixth current-carrying terminal adapted to receive a third bias current; and (6) a fourth transistor, comprising: (a) a fourth signal-receiving terminal adapted to be connected to a second voltage source, (b) a seventh current-carrying terminal connected to the fifth node, and (c) an eighth current-carrying terminal connected to the first node.

BRIEF DESCRIPTION OF THE DRAWINGS

Further objects, features, and advantages of the invention will become apparent from the following detailed description taken in conjunction with the accompanying figures showing illustrative embodiments of the invention, in which:

FIG. 1 is a schematic diagram illustrating a transconductor having dynamic biasing in accordance with the invention;

FIG. 2 is a schematic diagram illustrating an amplifier output stage having dynamic biasing in accordance with the invention;

FIG. 3 is a block diagram illustrating a feedback amplifier having a dynamically biased output stage in accordance with the invention;

FIG. 4 is a voltage graph illustrating the use of dynamic biasing to avoid crossover distortion in a circuit in accordance with the invention;

FIG. 5 is a block diagram illustrating the use of dynamic biasing applied to a low-pass input of a circuit in accordance with the invention;

FIG. 6 is a block diagram illustrating the use of dynamic biasing applied to the input of a circuit having an internal low-pass node in accordance with the invention;

4

FIG. 7 is a block diagram illustrating the use of an auxiliary circuit for dynamic bias in accordance with the invention;

FIG. 8a is a schematic diagram illustrating a first-order log-domain filter in accordance with the invention;

FIG. 8b is a schematic diagram illustrating a replica of the circuit of FIG. 8a, in accordance with the invention;

FIG. 9a is a block diagram illustrating a circuit having a differential output in accordance with the invention;

FIG. 9b is a block diagram illustrating a circuit having a single-ended output in accordance with the invention;

FIG. 10a is a graph of input current, and the envelope thereof, being received by a circuit in accordance with the invention;

FIG. 10b is a graph of differential output of a circuit in accordance with the invention;

FIG. 10c is a graph of voltage at a node within a circuit in accordance with the invention, wherein the circuit is dynamically biased;

FIG. 10d is a graph of voltage at a node within a circuit in accordance with the invention, wherein the circuit has a constant bias;

FIG. 10e is a graph of noise current of a circuit in accordance with the invention, wherein the circuit is dynamically biased;

FIG. 10f is a graph of noise current in a circuit in accordance with the invention, wherein the circuit has a constant bias;

FIG. 11 is a block diagram illustrating an envelope detector in accordance with the invention;

FIG. 12 is a schematic diagram illustrating a current-mode envelope detector in accordance with the invention;

FIG. 13 is a schematic diagram illustrating a current mirror circuit in accordance with the invention;

FIG. 14 is a schematic diagram illustrating a class-AB log-domain filter in accordance with the invention;

FIG. 15a is a block diagram illustrating a linear, lossy-low-pass filter;

FIG. 15b is a block diagram illustrating a companding low-pass filter having input-output characteristics similar to those of the filter of FIG. 15a;

FIG. 16 is a schematic diagram illustrating a circuit including the envelope detector of FIG. 12 coupled to a current mirror circuit in accordance with the invention;

FIG. 17a is a schematic diagram illustrating a band-pass filter;

FIG. 17b is a schematic diagram illustrating a band-pass filter having an auxiliary input for the introduction of dynamic bias in accordance with the invention;

FIG. 18 is a graph of simulated frequency response of the band-pass filter of FIG. 17b;

FIG. 19 is a schematic diagram illustrating an exemplary Tow-Thomas biquad circuit having band-pass and low-pass outputs;

FIG. 20a is a block diagram illustrating a log-domain filter;

FIG. 20b is a block diagram illustrating a log-domain filter with an input stage omitted;

FIG. 21 is a block diagram illustrating the use of a multiple-stage auxiliary circuit in accordance with the invention;

FIG. 22 is a schematic diagram illustrating a compensation circuit in accordance with the invention;

FIG. **23** is a schematic diagram illustrating a feedback arrangement in accordance with the invention;

FIG. **24** is a schematic diagram illustrating an amplifier in accordance with the invention; and

FIG. **25** is a schematic diagram illustrating a log-domain filter in accordance with the invention.

Throughout the figures, unless otherwise stated, the same reference numerals and characters are used to denote like features, elements, components, or portions of the illustrated embodiments. Moreover, while the subject invention will now be described in detail with reference to the figures, and in connection with the illustrative embodiments, changes and modifications can be made to the described embodiments without departing from the true scope and spirit of the subject invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **1** illustrates an example of a transconductor circuit which is dynamically biased in accordance with the invention. The circuit of FIG. **1** is powered by voltage sources V_{cc} and V_{L100}. It is to be noted that voltage (i.e., electrical potential) is inherently relative, and accordingly, the term "voltage source," as used herein, is defined to include ground (i.e., a voltage source producing a voltage of zero). In particular, in the circuit of FIG. **1**, either of V_{cc} and V_{L100} can be a connection to ground. The same is true for at least one voltage source in each of the circuits disclosed herein.

In the circuit of FIG. **1**, transistors Q_{102} and Q_{104} form a current mirror which sends current through transistors Q_1 and Q_2, respectively. The emitters of transistors Q_1 and Q_2 are connected by a resistor R_{106}. Each of transistors Q_1 and Q_2 is biased with a bias current I_E which flows through its current-carrying terminals—specifically its emitter and collector. The transconductor of FIG. **1** is operated in a differential mode in which the input voltage V_i is applied across the respective signal-receiving terminals (i.e., the base terminals) of the transistors Q_1 and Q_2. The transconductor produces an output current I_O.

If the transconductance of the bipolar transistors is much larger than $1/R_{106}$, the transconductance of the stage, I_O/V_i, becomes approximately equal to $1/R_{106}$, independently of I_E. Accordingly, I_E can be set at the minimum value required for a given signal. Specifically, a high value of I_E can be used for large signals, and a low value of I_E can be used for small signals.

In order to establish the most suitable bias of a signal processing circuit—such as, for example, a transconductor, an amplifier, or a filter—it can be desirable to base the bias upon a signal representing the amplitude or envelope of the signal being processed. The amplitude or envelope signal can be received from an external source, or can be generated using an envelope detector. A low-pass-filtered rectifier, well-known for use in many other applications, is one example of a circuit which can be used as an envelope detector.

It is to be noted that the circuit of FIG. **1** can also be reconfigured to have a topology in which the current sources I_E are connected to V_{cc}, the current mirror is connected to V_{L100}, the NPN transistors are replaced with PNP transistors, and the PNP transistors are replaced with NPN transistors.

The technique of the invention can also be employed in the output stage of an amplifier, an example of which is illustrated in FIG. **2**. The output stage of FIG. **2** is powered

by two voltage sources V_{DD} and V_{L200}. The circuit includes p-channel field effect transistors ("FETs") F_{202} and F_{204} which serve as current sources and are controlled by a bias voltage V_C. The bias voltage V_C is applied to the signal-receiving terminal—in this case, the gate—of each of p-channel transistors F_{202} and F_{204}. The bias currents flowing through the current-carrying terminals—in this case, the sources and drains—of p-channel FETs F_{202} and F_{204} are fed into respective drain terminals of n-channel FETs F_{206} and F_{208}. The gates of n-channel transistors F_{206} and F_{208} are connected by a resistor R_{210}. The gate and drain of FET F_{206} are connected together. An input voltage V_i is coupled to the gate of n-channel FET F_{208} through a capacitor C_{212}. An output voltage V_O and an output current I_O are generated at the connected drains of n-channel transistor F_{208} and p-channel transistor F_{204}. In accordance with the invention, the bias voltage V_c can be adjusted according to the input signal, such that F_{202} and F_{204} produce higher bias currents for larger signals and lower bias currents for smaller signals.

One method of feeding a signal into a circuit is through alternating current ("AC") coupling—for example, through a capacitor, as illustrated in FIG. **2**. However, other techniques can also be used. In the circuit of FIG. **2**, the transconductance of the stage will depend on the bias current. If there is high gain in front of this stage, and the entire circuit is operated in a closed-loop (i.e., feedback) mode, such bias-dependent transconductance need not have a large effect on the transfer function of the entire circuit. In addition, the stage can be reconfigured by using p-channel FETs in the circuit mirror and n-channel FETs to control the bias current; in such a reconfigured circuit, the sources of the p-channel FETs of the current mirror would be connected to V_{dd}, and the sources of the n-channel biasing FETs would be connected to V_{L200}.

In accordance with the invention, dynamically biased circuits can be designed as shown in FIG. **3**. In the circuit of FIG. **3**, an input signal u_3 passes through the positive input of a differencing block **302**, from which the difference signal d_3 passes to a gain stage **304** where it is amplified to produce an amplified signal w_3. In this example, the gain stage **304** is assumed to have a very large gain—ideally ∞. The amplified signal W3 enters a dynamically biased circuit **306** which generates an output signal y_3. The bias of the dynamically biased circuit **306** is controlled by a bias control **310**. A feedback path **308** connects the output of the dynamically biased circuit **306** to the negative input of the differencing block **302**. The difference signal d_3 seen by the gain stage is $u_3 - \beta y_3$, where β is the feedback factor ($\beta < 1$ for an amplifier). In the steady state of the feedback loop, the difference signal $d_3 = u_3 - \beta y_3$ is 0. This implies that the output attains a value $y_3 = u_3/\beta$. It is to be noted that the value of y_3 is independent of any quantity other than the input u_3. Therefore, it can be seen that the bias of the dynamically biased circuit has no effect on the output. As a result, disturbances due to bias changes are reduced due to the application of feedback.

In particular, when the bias of the dynamically biased circuit **306** is changed, the output tends to change. However, the changed output y_3, through the negative feedback loop **308** and the gain stage **304**, a change in the input w_3 of the dynamically biased circuit **306** in such a manner as to counteract the influence of the bias **310** and restore the output y_3 to its original value. An advantage of the circuit of FIG. **3**, as compared to a class-B circuit, is that the circuit of FIG. **3** produces no crossover distortion.

There are several ways in which one may configure dynamically biased circuit topologies. For example, a low-

7

pass class B or class AB circuit can be dynamically biased to avoid the crossover region, where large distortion usually occurs. An exemplary voltage characteristic of such a circuit is illustrated in FIG. 4. In this example, the average value of the input signal V_{in} is varied, so that $V_{in}(t)$ always stays clear of the high-distortion region of the voltage characteristic. By this technique, the bias is controlled to be sufficient to preserve the linearity of the circuit, but otherwise to be as small as possible so that low power dissipation—and in some circuits, low noise—is achieved.

Additional examples of circuits in accordance with the invention are illustrated in FIGS. 5 and 6. The circuit **502** of FIG. **5**, which can be, for example, a filter or an amplifier, is not a low-pass circuit. Therefore, because the bias tends to be slowly varying, it can be beneficial to apply the bias to a separate, low-pass input **504**, and to apply the signal being processed to the main input **506**, as shown in FIG. **5**. The circuit generates an output signal **508**.

FIGS. **17**a and **17**b illustrate an example of a type of filter, in this case a band-pass filter, which can be dynamically biased using a low-pass input in accordance with the invention. FIG. **17**a illustrates an exemplary band-pass filter having an input u_{bp} and an output y_{17}. The filter includes two resistors R_{173} and R_{174} and a capacitor C_{172} which serve as an input network. The filter also includes an amplifier **175** with a gain of –k, where k is a positive number—e.g., a positive integer. Feedback is provided by a feedback capacitor C_{171}.

FIG. **24** illustrates an example of an amplifier which can be used as the amplifier **175** in the circuit of FIG. **17**. The exemplary amplifier **175** includes transistors Q_{240}, and Q_{2402} and resistors R_{L1}, R_{E1}, and R_{E2}. The signal-receiving terminal (i.e., the base) of Q_{2401} receives an input voltage V_{i24}. The transistor Q_{2401} has current-carrying terminals—a collector and an emitter. The collector of Q_{2401} is connected to the signal-receiving terminal (i.e., the base) of transistor Q_{2402}, and is also connected to a voltage source V_{H24} through a resistor R_{L1}. The emitter of Q_{2401} is connected to another voltage source V_{L24} through an additional resistor R_{E1}. In the specific example illustrated in FIG. **24**, V_{H24} has a higher voltage than V_{L24}. Q_{2401}, R_{L1}, and R_{E1} form an emitter degenerated amplifier stage having a gain of –k, where $k=R_{L1}/R_{E1}$. The output voltage of this stage is the collector voltage V_{C2401} of Q_{2401}.

In the illustrated amplifier **175**, transistor Q_{2402} and resistor R_{E2} form an emitter follower stage having a gain of 1. The base of Q_{2402} receives the amplified voltage V_{C2401} from the collector of Q_{2401}. The collector of Q_{2402} is connected to voltage source V_{L24}. The emitter of Q_{2402} is connected to voltage source V_{H24} through resistor R_{E2}. The output voltage V_{024} of the emitter follower—which is also the output voltage of the entire amplifier **175**—is the voltage at the collector of Q_{2402}.

The gain –k of the amplifier **175** does not strongly depend on the bias currents I_{E2401} and I_{E2402} flowing through Q_{2401} and Q_{2402}, respectively. However, the bias currents I_{E2401} and I_{E2402} affect the size of the input voltage V_{i24} that can be accommodated by the amplifier **175**. Furthermore, a direct current ("DC") voltage component V_{inDC} of the input voltage V_{i24} can affect the bias currents I_{E2401} and I_{E2402}, as is demonstrated below.

The bias current I_{E2401} flowing the Q_{2401} is:

$$I_{E2401}=(V_{inDC}-V_{be24})/R_{E1},$$

8

where V_{be24} is the base-emitter voltage of the transistors Q_{2401} and Q_{2402}. The bias current I_{E2402} flowing through Q_{2402} is:

$$I_{E2402}=[(V_{inDC}-V_{be24})R_{L1}/R_{E1}-V_{be24}]/R_{E2}.$$

It can thus be seen that the bias currents I_{E2401} and I_{E2402} of the amplifier **175** can be controlled by adjusting the DC component V_{inDC} of the input voltage V_{i24} received by the amplifier **175**. For example, V_{inDC} can be reduced if the AC amplitude of V_{i24} is small, thereby reducing the bias currents I_{E2401} and I_{E2402}. Because of the reduced bias currents I_{E2401} and I_{E2402}, the amplifier **175** has reduced power consumption.

For the application of dynamic biasing to the circuit of FIG. **17**a, it might not be effective simply to add a bias to the input u_{bp}, because any DC components of u_{bp} are blocked, by C_{172}, from reaching the input of the amplifier **175**. In fact, in the circuit of FIG. **17**a, the DC gain from the input u_{bp} to the output y_{17} is essentially zero. However, in accordance with the invention, this circuit can be reconfigured to provide another input through which DC signals can reach the amplifier **175**. For example, as illustrated in FIG. **7**b, the originally grounded end of R_{174} can be disconnected from ground and used as an auxiliary input u_{1p}. From this auxiliary input u_{1p} to the output y_{17}, the filter has a low-pass characteristic. Accordingly, a dynamic bias—which tends to be slowly varying—can be applied to this input u_{1p}. FIG. **18** illustrates exemplary simulated transfer functions of the filter of FIG. **17**b, from the main and auxiliary inputs u_{bp} and u_{1p} to the output y_{17}. The component values used for the circuit simulation of FIG. **18** are: $R_{173}=R_{174}=1$ kΩ, $C_{171}=C_{172}=0.1$ μF, and k=8. As can be seen from FIG. **18**, the transfer function from the input u_{bp} of the filter to the output y_{17} vanishes at both low and high frequencies. However, the transfer function from the auxiliary input u_{1p} to the output y_{17} vanishes only for high frequencies. Specifically, in this example, it can be seen that the DC (i.e., very low frequency) gain is essentially zero for the main input u_{bp} and 1 for the auxiliary input u_{1p}.

If a circuit comprises a low-pass circuit **602**, as illustrated in FIG. **6**, it is possible to have the same input **604** for both the bias **610** and the signal **612**, yet separate outputs **606** and **608**. The bias **610** and the signal **612** can, optionally, be combined using a voltage adder **614**, to thereby generate the input signal **604**. Furthermore, although the intended output of the circuit **602** may not be low-pass, some internal portions of the circuit can, in some cases, be adjusted even if the bias control is itself low-frequency. Such a technique can be used, for example, in topologies derived from the Tow-Thomas biquad.

An example of such a biquad circuit is illustrated in FIG. **19**. The circuit receives an input voltage u_{19} and generates a band-pass output voltage y_{bp} and a low-pass output voltage y_{1p}. The input signal u_{19} is fed through an input resistor R_{1904} to the negative input terminal of a first amplifier **1918**, which produces the band-pass output voltage y_{bp}. A feedback circuit including a resistor R_{1902} and a capacitor C_{1914}, connected in parallel, provide coupling between the output and negative input of the first amplifier **1918**. The band-pass output signal y_{bp} is fed through a resistor R_{1912} into the negative input of a second amplifier **1920**, which generates the low-pass output voltage y_{1p}. A feedback capacitor C_{1916} connects the output and negative input of the second amplifier **1920**.

Finally, a feedback circuit connects the low-pass output y_{1p} with the negative input terminal of the first amplifier **1918**. The feedback circuit includes a third amplifier **1922**

and three resistors R_{1910}, R_{1908}, and R_{1906}. Resistor R_{1910} connects the low-pass output y_{1p} with the negative input of the third amplifier **1922**. The output of the third amplifier **1922** is connected, through R_{1906}, to the negative input of the first amplifier **1918**. Resistor R_{1908} connects the output and negative input of the third amplifier **1922**. It is to be noted that any or all of the amplifiers **1918**, **1920**, and **1922** shown in FIG. **19** can comprise the amplifier **175** illustrated in FIG. **24**. The amplifier **175** of FIG. **24** has been discussed extensively above for use in the circuits of FIGS. **17a** and **17b**.

In accordance with the invention, a dynamic bias can be applied to the band-pass output—which can also serve as a low-pass input—of the circuit of FIG. **19**. Such a technique allows adjustment of the low-pass portion of the circuit (which includes the second amplifier **1920**), thereby providing benefits such as increased energy efficiency, reduced noise, and increased dynamic range, as discussed above.

In some filters it may not be possible to adequately control multiple points within a filter from a single bias input, because the individual transfer functions of various portions of the circuit may be different. In such a case, it can be beneficial to use an auxiliary circuit such as shown in FIG. **7**, and feed individual bias control signals **706** to multiple points in the main circuit. The auxiliary circuit **702** can be approximately similar to the main circuit **704**. Individual envelope or mean value extraction circuits can, optionally, be used to generate the various outputs **706**. The auxiliary circuit **702** can, optionally, be a low-pass equivalent of the main circuit **704**, and can be fed by the envelope (or mean value, etc.) of the input **708**, such that the individual bias control signals **706** are delayed by suitable amounts before being fed to the main circuit **704**. In particular, if the main circuit **704** is a filter, there are typically phase shifts at the various internal nodes. The auxiliary circuit **702** preferably mimics these phase shifts such that the bias control signals **706** adjust the respective internal nodes of the main circuit **704** using the correct phases.

FIG. **21** further illustrates the use of such an auxiliary circuit. The auxiliary circuit **702** of FIG. **21** includes multiple stages **2102** which can, optionally, be essentially identical to the multiple stages **2106** of the main circuit **704**. Each of the stages **2102** of the auxiliary circuit produces an output signal **2108** which can be essentially identical, in both amplitude and phase, to the intermediate signals **2110** present between the respective stages **2106** of the main circuit **704**. Each of the output signals **2108** is sent into its own envelope detector **2104** which generates a bias control signal **706** for the appropriate portion of the main filter **704**. Because the auxiliary circuit **702** matches the main circuit **704**, any phase or time shifts present in the main circuit **704** are also present in the respective outputs **2108** of the auxiliary circuit **702**. As a result, each of the bias control signals **706** is phase or time shifted by the proper amount.

It may be desirable to use two matching versions of a signal-processing circuit, each fed by different polarity signals, with the outputs of the two versions being subtracted so that the bias component cancels out, as described in further detail below with respect to a particular log-domain circuit. In another embodiment, the signal and bias can be fed to one circuit, while the second circuit receives only the bias.

In accordance with an additional embodiment of the invention, an externally linear time-invariant filter—which can be internally non-linear—can be biased dynamically (i.e., variably) in accordance with the signal so that large signals do not overload the filter, and small signals are not

buried under noise. For example, a log-domain filter can be biased in such a manner, and dynamic biasing can be used for other types of filters as well.

FIG. **8a** illustrates an example of a first-order, log-domain, low-pass filter. Such a filter generally operates by performing a logarithm operation upon an input signal, filtering the resulting logarithmic signal, and performing an exponential (i.e., anti-logarithm) operation upon the filtered signal to restore the filtered, logarithmic signal to an output signal which is linearly related to the input signal. A log-domain filter is considered a "companding" filter because it first compresses the signal and then expands it. Generally, companding filters are internally non-linear, yet they can be designed to be externally linear—i.e., the output being linear with respect to the input.

The concept of companding is further illustrated by FIGS. **15a** and **15b**. FIG. **15a** illustrates an exemplary linear first order filter. In the filter of FIG. **15a**, an integrator **1502** having a gain constant k is connected in a negative feedback loop with an amplifier **1504** having a gain of a/k. Negative feedback is provided using a differencing block **1506**. The resulting circuit is a low-pass filter having the following transfer function:

$$H(s) = \frac{Y(s)}{U(s)} = \frac{k}{s+a}$$

which generally describes a low-pass filter having a bandwidth of a rad/s. FIG. **15b** illustrates a general companding equivalent of the low-pass filter in FIG. **15a**. A nonlinearity block **1512** having a non-linear function $f(v)$ is used to provide the output y, and an amplifier **1508** having a gain of $1/f'(v)$, where $f'(v)$ is the derivative of $f(v)$, is used at the input. $f(v)$ serves as an expander, and the amplifier with gain $1/f'(v)$ serves as a compressor. For example, in a log-domain filter, $f(v)$ would be an exponential function. The compressor and expander, together with a modified feedback path **1510**, form a low-pass filter that is equivalent to the linear filter of FIG. **15a** and realizes the transfer function H(s) given above. The relation between the input u and the intermediate variable v is non-linear in FIG. **15b**.

In the case of the circuit of FIG. **8a**, assuming that all of the transistors are ideal (i.e., that their base currents are zero or negligible), the input portion of the circuit, formed by transistors Q_{1p} and Q_{2p}, has a logarithmic voltage/current characteristic. Specifically, the base-emitter voltage of Q_{2p}, V_{be2p}, is approximately constant, and the base-emitter voltage of Q_{1p}, V_{be1p}, is proportional to the logarithm of the normalized input currents: $V_{be1p}=V_t ln[(i_{in}+I_{bias})/I_s]$. Therefore, the base voltage of Q_{2p}, V_{b2p}, is:

$$V_{b2p}=V_{be2p}+V_t ln[(i_{in}+I_{bias})/I_s].$$

where V_t is the thermal voltage of Q_{2p} and I_s is the saturation current of Q_{2p}.

The filter uses transistor Q_{3p} to send the logarithmic component of V_{b2p} into the base of transistor Q_{4p}. At low frequencies, the output portion of the circuit, formed by transistor Q_{4p}, produces a current i_{4p}, into the collector of Q_{4p}, which is exponentially related to the base voltage of Q_{4p}:

$$i_{4p}=Kexp\{ln[(i_{in}+I_{bias})/I_s]\}=K[(i_{in}+I_{bias})/I_s].$$

where K is a constant.

Accordingly, the relationship between the input signal i_{in} and the output signal i_{outp} is ultimately linear. Low-pass filtering is provided by a high-frequency shunt—in this case,

the capacitor C_{1p}—which shorts out high-frequency signals at the base of Q_{4p}. Ideally, in a log-domain filter, the relationship between the large signal currents i_{1p} and i_{4p} in the input and output transistors Q_{1p} and Q_{4p}, respectively, is linear and time invariant—assuming that i_{1p} is always positive. Assuming that the base currents of Q_{2p} and Q_{3p} are negligible, i_{1p} is the sum of an AC input signal i_{in} and a bias current I_{bias}. I_{bias} is typically constant. The output i_{outp} is obtained by subtracting $(I_{2p}/I_{3p})I_{bias}$ from i_{4p}. I_{2p}/I_{3p} is the DC gain of the filter.

In accordance with the invention, dynamic biasing can be applied to circuits such as the filter of FIG. 8a, by varying I_{bias} in accordance with the envelope of the input i_{in} so that I_{bias} is slightly larger than the minimum value required to keep i_{1p} positive at all times. Such dynamic biasing lowers the power consumption and the output noise of the filter for small inputs, while enabling the circuit to accommodate very large inputs without excessive distortion.

Dynamic biasing also alters the "gain" from the input current to the internal voltages. Gain alteration has also been used for syllabic companding, which involves slowly varying the gain of an input amplifier in order to accommodate varying signal sizes and to maintain a relatively constant-amplitude output signal. However, dynamic biasing is simpler to implement than syllabic companding. On the other hand, in dynamic biasing systems, the time varying I_{bias} is filtered along with the input signal, and is also included in the output signal. Accordingly, i_{outp} is no longer merely a filtered version of i_{in}, but also includes a filtered version of I_{bias}. Consequently, it can be preferable to use a compensation circuit for some applications, in order to compensate for the presence of the filtered I_{bias} signal in the output signal.

An example of such a compensation circuit is illustrated in FIG. 22. The circuit of FIG. 22 is similar to the circuit for which compensation is desired—i.e., the circuit of FIG. 8a. In particular, the compensation circuit of FIG. 22 includes transistors Q_{2201}, Q_{2202}, Q_{2203}, and Q_{2204}, which behave similarly to the transistors Q_{1p}, Q_{2p}, Q_{3p}, and Q_{4p}, respectively, of the filter of FIG. 8a. Capacitor C_{2210} of FIG. 22 provides low-pass filtering similarly to capacitor C_{1p} of FIG. 8a. However, the compensation circuit of FIG. 22 includes an additional transistor Q_{2206} which mirrors the current flowing through Q_{2203}. The emitter current I_x of Q_{2206} is fed into the node 82 (in FIG. 8a) to which the emitter of Q_{3p} is connected. A current source I_{min} provides bias current into the collector of Q_{2201}.

The compensation circuit receives, into the collector of Q_{2201}, the envelope I_E of i_{in}, rather than i_{in} itself. For larger amplitude input signals, I_E increases, causing an increase in the current flowing through Q_{2203}. The increased current in Q_{2203} causes an increase in the current I_x which flows into node 82 of the filter of FIG. 8a, thereby increasing the base voltage of Q_{4p}. As a result, the quiescent (i.e. bias) current flowing through Q_{4p} is increased, thereby enabling the exponentiator stage of the filter of FIG. 8a to accommodate the larger input signal i_{in} which is being received.

If the amplitude of i_{in} decreases, I_E decreases, which reduces I_x. The voltage at node 82 drops, thereby decreasing the bias current flowing through Q_{4p}. Consequently, power consumption and shot noise are reduced for input signals having smaller amplitudes.

Moreover, there is an additional method for distortionless dynamic biasing. In accordance with the invention, a single-ended filter such as the circuit illustrated in FIG. 8a is duplicated. The duplicate circuit is operated with the same bias I_{bias} but an inverted input $-i_{in}$ as shown in FIG. 8b.

The duplicate circuit, an example of which is illustrated in FIG. 8b, includes transistors Q_{1n}, Q_{2n}, Q_{3n} and Q_{4n} which

correspond to transistors Q_{1p}, Q_{2p}, Q_{3p}, and Q_{4p} of the original circuit, illustrated in FIG. 8a. The circuit of FIG. 8b also includes current sources I_{2n} and I_{3n}—which are of approximately equal value to I_{2p} and I_{3p}, respectively, of the original circuit. Capacitor C_{1n} of the duplicate circuit is approximately equal in value to C_{1p} of the original circuit. The output transistor currents i_{4p} and i_{4p} in the respective filters of FIGS. 8a and 8b can be written as:

$$i_{4p}(t)=(i_{in}(t)+I_{bias}(t))*h(t); i_{4n}(t)=(-i_{in}(t)+I_{bias}(t))*h(t), \qquad (1)$$

where h(t) is the impulse response of each filter (i.e., the impulse response between i_{1p} and i_{4p}, and between i_{1n} and i_{4n}, where all base currents are assumed to be zero or negligible) and "*" denotes convolution. In the differential output $i_{out}=i^{4p}$—i_{4n}, the bias dependent term $I_{bias}(t)*h(t)$ cancels out, giving the result: $i_{out}(t)=2i_{in}(t)*h(t)$. The relation between i_{out} and i_{in} is therefore linear and time invariant, and is the same (except for a factor of 2) as that between i_{outp} and i_{in} in the original log-domain filter (the circuit of FIG. 8a) operating with a constant bias. No extra circuitry is required to compensate for the effect of I_{bias}, because I_{bias} is not present in the output.

In accordance with the invention, a dynamically biased log-domain filter can be operated pseudo-differentially to cancel the effects of time varying bias, as illustrated in FIG. 9a. For example, two matching circuits 902 and 904—which can be, for example, the circuits of FIGS. 8a and 8b—can be used in the differential configuration illustrated in FIG. 9a. The input signal of such a configuration would be $2i_{in}$, and the output signal would be i_{4p}-i_{4n}. Such a configuration can eliminate the need to provide a bias current of $(I^{2p}/I_{3p})I_{bias}$ into transistor Q_{4p}, or a bias current of $(I^{2n}/I_{3n})I_{bias}$ into transistor Q_{4n}. Furthermore, structures that operate using differential input (e.g. certain class-AB circuits) can also be used in FIG. 9a. Such a differential circuit 908 is represented by the dotted lines of FIG. 9a.

In addition to cancellation of the bias dependent terms, pseudo-differential operation has benefits such as cancellation of even-order non-linearities and common mode interferences. For example, if the elements of a circuit are non-ideal—e.g., if the transistors in a log-domain filter have characteristics which deviate from ideal logarithms and exponentials—the input and bias signals can interact with the non-idealities to generate harmonics, especially even-order harmonics. Because even-order harmonics have the same sign and approximately the same values in both halves of a pseudo-differential circuit, these harmonics cancel, thereby providing improved signal quality.

Furthermore, if I_{bias} contains noise, approximately the same noise signal, with the same sign, is present in each half of the circuit. Consequently, noise signals introduced by I_{bias} are cancelled in the differential output. In contrast, the input signal i_{in} is present with opposite signs in the respective halves of the circuit. Therefore, the input signal is not canceled in the differential output. As a result, the circuit of FIG. 9a provides an improved signal-to-noise ratio.

In accordance with another aspect of the invention, the scheme shown in FIG. 9b, in which the second filter 904 receives only the bias signal, can be used. The technique of supplying the input signal to only one of the filters can be advantageous for applications in which single-ended input is desired. Either of the arrangements of FIGS. 9a and 9b can, optionally, include a differencing block 906 at the output, which can be advantageous for applications in which single-ended output is desired. Single-ended input and/or output can be desirable for, e.g., for proper interfacing with other circuits.

The linear time-invariant relation between the input and output transistor currents in a log-domain filter enables the cancellation of time varying bias components at the output. In contrast, if time varying gains are placed before and after a classical linear filter, pseudo-differential operation does not result in a linear time-invariant system.

The base emitter voltage of Q_{1p} in FIG. 8a is given by: $V_{belp}=V_t\ln[(i_{in}+I_{bias})/I_s]$. An increase in the envelope of i_{in} by a factor α causes I_{bias} to increase by the same factor because I_{bias} is derived from the envelope of i_{in}. In other words, i_{in1} becomes $i_{in2}=\alpha i_{in1}$ and I_{bias1} becomes $I_{bias2}=\alpha I_{bias1}$, where i_{in1} and I_{bias1} are the initial values of i_{in} and I_{bias}, and i_{in2} and I_{bias2} are the new values. Therefore, V_{belp1} (the initial value) becomes V_{belp2} (the new value):

$$V_{belp2}=V_t\ln[\alpha(i_{in1}+I_{bias1})/I_s]=V_t\ln[(i_{in1}+I_{bias1})/I_s]+V_t\ln(\alpha)=V_{belp1}+V_t\ln(\alpha).$$

It can thus be seen that V_{belp} undergoes only a DC shift equal to $V_t\ln(\alpha)$. Because of the linearity between i_{1p} and i_{4p}, it can be seen that V_{be4p} also undergoes only a DC shift. Therefore, the AC signal applied to the voltage-mode filter 802 between the input and output transistors (enclosed by dashed lines in FIG. 8a) remains the same regardless of the input signal strength if dynamic biasing is used. This confirms the analogy of dynamic biasing to syllabic companding. Like syllabic companding, dynamic biasing also increases the dynamic range of a log-domain filter.

FIG. 14 illustrates an exemplary class-AB instantaneous companding log-domain filter which can be dynamically biased in accordance with the invention. The filter of FIG. 14 incorporates log-domain filters similar to those of FIGS. 8a and 8b, in accordance with the invention. The left half of the filter includes transistors Q_{1p} and Q_{2p} which perform a logarithm operation upon the signal up entering the left half. Transistors Q_{3p} and Q_{4p} restore the left half of the signal to linearity by performing an exponential operation upon the logarithmic signal. Capacitor C_{1p}, which serves as a high-frequency shunt, provides low-pass filtering. Q_{2p} is biased with a bias current I_{2p}, and Q_{3p} is biased with a bias current I_{3p}. The right half of the filter includes components Q_{1n}, Q_{2n}, Q_{3n}, Q_{4n}, and C_{1n} which perform the same functions—in the right half—as Q_{1p}, Q_{2p}, Q_{3p}, Q_{4p} and C_{1p} perform in the left half. The two halves of the filter are cross-coupled using transistors Q_{5p} and Q_{5n}.

The difference current u_p-u_n is the input to the filter, and the difference current y_p-y_n is the output. The filter can operate in a class-AB mode in which the left half of the circuit handles positive portions of the input signal—i.e., when u_p is positive and u_n is negative—and the right half handles negative portions of the input signal—i.e., when u_p is negative and u_n is positive.

FIGS. 10a–10f illustrate the results of a simulation, in accordance with the invention, of an exemplary pseudo-differential configuration of the low-pass filters of FIGS. 8a and 8b, where the combined filter was configured to have a –3dB frequency of 100 kHz ($I_{2p}=I_{3p}=1$ μA, $C_{1p}=61.5$ pF). The input was a sinewave with a changing envelope (FIG. 10a). The circuit was simulated in two different modes of operation: (i) with a dynamic bias 10% larger than the changing envelope, and (ii) with a constant bias 10% larger than the largest envelope (the largest envelope being 2 μA, as illustrated in FIG. 10a). The constant bias case corresponds to classical class-A operation. The outputs of the filter in the two different modes are plotted in FIG. 10b and are identical in this simulation. FIGS. 10c and 10d show the base emitter voltage of Q_{4p} (a voltage internal to the filter) in the two cases. Syllabic companding is clearly seen in FIG.

10c—the internal voltage swing is constant regardless of the input amplitude. With a constant bias, the amplitude of the internal voltage varies with the input current, as can be seen in FIG. 10d. The results of transient noise simulations are shown in FIGS. 10e and 10f. It is evident from these figures that dynamic biasing provides noise reduction for small input signals. These results demonstrate the external linearity and syllabic companding nature of the dynamically biased filter.

The technique of the invention provides several advantages over conventional circuits. First, compensation circuits used in conventional circuits require extra design effort, in some cases as much as for the main filter, and add to the power consumption and noise of the overall filter. In contrast, the method of the invention—illustrated by example in FIG. 9a—has no additional design overhead because the required filter is simply duplicated. Furthermore, the technique of the invention introduces no additional power consumption or noise because there is no "extra" circuitry other than the filter used to differentially process the input signal.

FIG. 25 illustrates an additional example of a log-domain filter which can be dynamically biased in accordance with the invention. Similarly to the log-domain filter of FIG. 8a, the log-domain filter of FIG. 25 can be used in one or both of filter blocks 902 and 904 of the circuits of FIGS. 9a and 9b. The filter of FIG. 25 receives an input signal u_{2500} which, if the filter is used in block 902 of one of the circuits of FIGS. 9a and 9b, equals $i_{in}+I_{bias}$. Transistors Q_{2501}, Q_{2502}, and Q_{2503} are biased with currents I_{bias}, I2502, and I_{2503}, respectively. The output signal y_{2500} is the collector current of transistor Q_{2504}. The emitters of Q_{2501} and Q_{2503} are connected to each other, as are the emitters of Q_{2502} and Q_{2504}. A bias voltage V_{25bias} fixes the base voltages of Q_{2501} and Q_{2504}. The bases of Q_{2502} and Q_{2503} are connected to each other, and are also connected to V_{25bias} through a capacitor C_{2510}.

A FET F_{2506} is used, in a feedback arrangement, to control the current flowing through Q_{2501}. The FET F_{2506} serves as a regulated current source. The source terminal of F_{2506} is connected to a voltage source V_{L25}. The drain of F_{2506} is connected to the emitter of Q_{2501}. The gate of F_{2506} is connected to the collector of Q_{2501}. If Q_{2501} is in a region of its operating characteristic—i.e., its current-voltage characteristic—in which its collector current would tend to exceed u_{2500}, the collector voltage of Q_{2501} drops, causing the gate voltage of F_{2506} to drop. The drop in gate voltage causes the drain current of F_{2506} to decrease, which increases the emitter voltage of Q_{2501}. The increase in emitter voltage decreases the base-emitter voltage V_{be2501} of Q_{2501}, which tends to cause a decrease in the collector current of Q_{2501}. If, on the other hand, Q_{2501} is in a region of its operating characteristic in which its collector current would tend to be less than u_{2500}, the opposite result occurs: V_{be2501} is increased, which tends to cause an increase in the collector current of Q_{2501}. In equilibrium, the collector current and base-emitter voltage V_{be2501} of Q_{2501} are thus regulated to maintain the transistor Q_{2501} in a region of its operating characteristic in which the collector current of Q_{2501} is exponentially dependent upon the base-emitter voltage V_{be2501}, and in which the base-emitter voltage V_{be2501} is logarithmically related to the collector current of Q_{2501}.

As a result, Q_{2501} performs a logarithm operation on u_{2500}, thereby generating V_{be2501}. Because the base voltage of Q_{2501} is fixed by V_{25bias}, the resulting logarithm signal is present at the emitters of Q_{2501} and Q_{2503}. Because the base

15

and collector of Q_{2503} are connected together, Q_{2503} acts as a diode which communicates the logarithm signal to the base of Q_{2502}. High-frequency signal components are suppressed by a high-frequency shunt—in this case, capacitor C_{2510}— connected between the base of Q_{2502} and voltage source V_{25bias}. Q_{2502} is biased by a current I_{2502}. The collector current and base-emitter voltage of Q_{2502} are regulated by a FET F_{2508} which operates similarly to the FET F_{2506} which regulates the collector current and base-emitter voltage V_{be2501} of Q_{2501}.

Transmitter Q_{2502} communicates the low-pass-filtered, logarithm signal from the base of Q_{2502} to the emitter of Q_{2502}, this emitter being connected to the emitter of Q_{2504}. Because the base voltage of Q_{2504} is fixed by voltage source V_{25bias}, the filtered, logarithm signal is induced in the base-emitter voltage V_{be2504} of Q_{2504}. Because the output signal y_{2500} is exponentially related to V_{be2504}, transistor Q_{2504} exponentiates the filtered, logarithm signal which is present in V_{be2504}, thereby restoring the signal to linearity. Consequently, y_{2500} is linearly related to u_{2500}. The transfer function between y_{2500} and u_{2500} is:

$$H_{2500}(S)=Y_{2500}(S)/U_{2500}(S)=(I_{2502}/I_{2503})/(1+sC_{2510}V_t/I_{2503}),$$

where V_t is the thermal voltage of the various transistors in FIG. 25.

Even if the current gains of the transistors are finite, the only base current that significantly affects the operation of the circuit is that of Q_{2502}. However, the base current of Q_{2502} is a constant $I2502/\beta$ which is subtracted from I_{2503}. Consequently, no significant additional nonlinearity is introduced into the circuit, and the only effect of the finite β—assuming that β is constant with respect to the collector currents—is a reduction of the bandwidth of the filter. If this bandwidth reduction is undesirable, it can be counteracted either by injecting a current $I2502/\beta$, as illustrated in FIG. 25, or by using automatic tuning techniques known to those skilled in the art.

Instantaneous companding via class-AB or class-B operation is another technique which has been used to realize high dynamic range log-domain filters. In this technique, a differential filter receives an input signal which equals the difference of half-wave rectified or geometrically split currents.

However, the technique of the invention provides several advantages over class-AB instantaneous companding. For example, in a preprocessing circuit in accordance with the invention, the accuracy of the envelope detector is less important, provided that its output is larger than the actual envelope. In contrast, a class-AB splitter generally must accurately reproduce the input signal in the splitter's difference output in order to avoid added distortion. For at least this reason, the envelope detector of the invention is simpler to design than a class-AB splitter. Furthermore, in conventional circuits, mismatch of circuit elements can lead to distortion because of internal non-linearity (in class-AB filters) and incomplete cancellation of bias components (in dynamically biased filters). For example, various frequency components of the input signal can interact with circuit nonlinearities to cause intermodulation distortion, i.e., spurious signals at various sum and difference frequencies of the various frequency components. In fact, in a conventional companding filter, if internal components deviate from their ideal nonlinear (e.g., ideal logarithm or ideal exponential) characteristics, such deviation can also result in distortion. In contrast, circuits in accordance with the invention tend to produce slowly varying bias components which, in many cases, can be more acceptable than intermodulation distor-

16

tion. In addition, noise from the envelope detector of the invention cancels at the output of the filter. In contrast, the two outputs of a conventional class-AB splitter contain noise in opposite phases of the input for large signals; such noise does not cancel at the filter's output, and the uncanceled noise can degrade the signal-to-noise ratio of the filter.

The bias I_{bias} in FIGS. 8a, 8b, 9a, 9b, and 25 can be generated using an envelope detector which can be, for example, a current mode envelope detector in accordance with the invention. FIG. 11 provides a block diagram of such a circuit. The output y of the detector is subtracted from the input u of the detector using a differencing block 1106. The output u-y of the differencing block 1106 is fed into an exponentiating block 1102 to produce an exponentiated error u_f. A low pass filter 1104 having a cutoff frequency ω_p filters the exponentiated error u_f to produce the output y.

To better understand the operation of the envelope detector of FIG. 11, it is useful to consider a case in which the input u is a sine wave having an angular frequency much larger than ω_p, and the output y is less than the envelope of u. During the portions of the input cycle in which u exceeds y, the output u_f of the exponential becomes extremely large. Because of the large signal entering the low-pass filter, the output y rapidly increases to reach u. As the cycle proceeds, the input u falls below the output y. The exponentiating block 1102, whose input u-y is now negative, reduces its output u_f to a very small value, close to zero, which in turn causes the output y of the low-pass filter 1104 to drop exponentially at a rate determined by its time constant. Since the low-pass filter's time constant is much longer than the input period, y does not drop appreciably in one cycle of the input u. Therefore, in steady state, the output y stays very close to the peak value of the input u, with a small drop between successive input peaks. If the input amplitude drops appreciably, the error u-y is constantly negative and the input u_f of the low-pass filter is therefore essentially zero. The output y falls exponentially until it reaches the new, reduced, peak value of the input u. On the other hand, an increase in the input amplitude causes the input u_f of the low pass filter to be very large due to the exponentiation of a positive quantity, and y therefore rises rapidly to reach the new peak value. This "fast attack" behavior is desirable, since, in a dynamically biased filter, the bias is preferably kept larger than the input in order to avoid distortion.

FIG. 12 illustrates an example of a circuit realization, in accordance with the invention, of the envelope detector of FIG. 11. In the detector 1200 of FIG. 12, the input signal and the output envelope are current-mode signals. However, voltage-mode signals can also be received and generated by, e.g., adding simple current-voltage converters. For example, a transconductor such as the circuit of FIG. 1 can be used to convert a voltage-mode signal to a current-mode signal.

The emitter voltage V_{e121} of transistor Q_{121} in FIG. 12 can be written as:

$$V_{e121}=V_{err}-V_t\ln(I_{121}/I_s),$$

where I_s is the saturation current of Q_{121}.

The circuit comprising transistors Q_{121} Q_{122}, Q_{123}, and Q_{124}, the capacitor C_{126}, and the bias sources I_{121}, I_{122}, and I_{123} acts as a low-pass filter governed by the following equation:

$$\frac{d\,I_{124}}{d\,t} = -\frac{I_{122}}{C_{126}\,V_t}I_{124} + \frac{I_{123}}{C_{126}\,V_t}I_{121}\exp\!\left(\frac{V_{bias} - V_{err}}{V_t}\right).$$

The last term in the above equation denotes the input to the low-pass filter. V_{err} appears in the argument of the exponential. This circuit can therefore perform the combined functions of the exponentiator **1102** and low-pass filter **1104** of FIG. **11** if V_{err} is made proportional to the error between the input and the output.

The output I_{124} is subtracted from the input fin at the collector node of Q_{124}. If I_{in} is larger than I_{124}, the collector voltage of Q_{124} increases, and if I_{in} is smaller than I_{124}, the collector voltage of Q_{124} decreases. The voltage swing at the collector of Q_{124} is limited by a voltage-limiter. In the particular circuit of FIG. **12**, the voltage-limiting function is performed by diodes D_1 and D_2. The error voltage thus generated at the collector is inverted by the amplifier A—in order to obtain the correct sign for feedback—and fed to the base of Q_{121} as V_{err}.

In order to tap the output, the bases Of Q_{123a} and Q_{124a} are connected to the bases of Q_{123} and Q_{124}, respectively. Transistor Q_{124a} is fabricated with a cross-sectional area α times larger than Q_{124} in order to ensure a safety margin in the bias current fed to the log-domain filters. The term "cross-sectional area," as used herein, can include the collector area and/or the emitter area of a transistor, depending on the particular device- fabrication technology used to form the transistors. PNP transistors Q_{127} and Q_{128} are used to mirror αI_{124} as required, thereby providing dynamically controlled bias currents for one or more nodes of a main circuit for which dynamic biasing is desired. An exemplary embodiment of the inverting amplifier A is illustrated in inset **1204** of FIG. **12**. The amplifier A includes p-channel FETs F_{12a} and F_{12b} which form a current mirror, as well as amplifying n-channel FETs F_{12c} and F_{12d}. The sources of F_{12c} and F_{12d} are connected by a resistor R_{12a}. The drain of F_{12c} is connected to the bias voltage V_{bias} of the envelope detector through a resistor R_{12b}, which serves as an output load for the amplifier. FETs F_{12c} and F_{12d} are biased by bias currents I^{S12a} and I^{S12b}, respectively.

When the amplifier A is used as part of the envelope detector of FIG. **12**, the collector voltage V_{in} of transistor Q_{124} is fed into the gate of n-channel FET F_{12c}. Because the amplifier A operates in a differential mode, its output V_{err} is proportional to the difference between V_{bias} and V_{in}.

FIG. **12** also illustrates an exemplary embodiment of a feedback arrangement **1202** which can be used to drive bias currents I_{121} and I_{123} through Q_{121} and Q_{123} in a controlled manner. The transistor in Q_{11a} in the feedback arrangement **1202** represents a transistor through which a regulated current is to be driven—e.g., one of the transistors Q_{122}, Q_{123}, or Q_{124} in FIG. **12**. The operation of the feedback arrangement **1202** can be readily understood by considering FIG. **23**, in which the n-channel FET F_{11}, the NPN transistor Q_{11b}, and current source I_{11} are modeled as a voltage-controlled current source I_{fb}. If the control voltage v_{fb} increases, the current through I_{fb} increases. If the collector current I_{c11} of the transistor Q_{11a} tends to be smaller than the current I_{12}, the collector voltage of Q_{11a} which is also the control voltage v_{fb}, tends to increase. This increased v_{fb} increases the current through I_{fb}, which in turn draws a larger current through Q_{11a}. The opposite effect—i.e., a decrease in v_{fb} and the current through I_{fb}—occurs when the collector current I_{c11} tends to be larger than I_{12}. The circuit settles at a point where $I_{C11} = I_{12}$.

F_{11}, I_{11}, and Q_{11b} emulate I_{fb}. F_{11} and I_{11} form a source follower with near-unity gain that simply translates the collector voltage to a suitable level for driving Q_{11b}. The level-shifted voltage is converted into a current using the transistor Q_{11b}. The circuit settles to a point where $I_{C11} - I_{12}$

FIG. **13** illustrates an example of an inverting current mirror which can be used to connect a dynamic bias control circuit (e.g., an envelope detector) to a signal-processing circuit (e.g., an amplifier, a transconductor, or a filter) which requires bias current to flow out of, not into, the signal processing circuit. For example, the current mirror of FIG. **13** can be used to connect the envelope detector of FIG. **12** to the transconductor circuit of FIG. **1**.

The current mirror of FIG. **13** is powered by voltage sources V_{H13} and V_{L100}. Transistor Q_{127} (also illustrated in FIG. **12**) is driven by output current αI_{124} of the envelope detector of FIG. **12**. The base of PNP transistor Q_{128} (also illustrated in FIG. **12**) is connected to the base of PNP transistor Q_{127}, and accordingly, the current $\beta_{13}I_{124}$ flowing through Q_{128} (where β_{13} is a constant) is proportional to the current αI_{124} flowing through Q_{127}. The current $\beta_{13}I_{124}$ from Q_{128} flows into the collector of a diode-connected (i.e., base and collector of transistor connected together) NPN transistor Q_{1302}. The base and collector of Q_{1302} are connected to the respective bases of output transistors Q_{1304}. The output currents $\gamma_{13}I_{124}$ and $\delta_{13}I_{124}$ of the output transistors Q_{1304} mirror the current $\beta_{13}I_{124}$ flowing through Q_{1302}, which in turn mirrors the current αI_{124} flowing through Q_{127}—αI_{124} being the output of the envelope detector of FIG. **12**. It can therefore be seen that the output currents $\gamma_{13}I_{124}$ and $\delta_{13}I_{124}$ of the current mirror of FIG. **13** ultimately mirror the output current αI_{124} of the envelope detector of FIG. **12**. Furthermore, output currents $\gamma_{13}I_{124}$ and $\delta_{13}I_{124}$ flow in the proper direction—i.e., with the current flowing in, not out—to provide the bias current I_E to a circuit such as the transconductor of FIG. **1**. The constants γ_{13} and δ_{13} depend upon the device characteristics—e.g., the relative cross-sectional areas—of transistors Q_{124}, Q_{124a}, Q_{127}, Q_{128}, Q_{1302}, and Q_{1304}.

In order to utilize the envelope detector of FIG. **12** to control the bias of a differential circuit such as the transconductor of FIG. **1**, it can be desirable to feed only the positive side, or only the negative side, of differential voltage signal V_i into the non-differential input current signal I_{in} of the envelope detector. For example, one side of the voltage-mode signal V_i can be fed into the input of the detector through a resistor, in order to produce the current-mode signal I_{in}. Alternatively, V_i can be converted to a current-mode signal using a transconductor. For example, the conversion can be performed using a non-dynamically biased version of a circuit having a topology similar to the transconductor of FIG. **1**, but in which I_E is kept constant, rather than being adjusted as described above. Such a circuit can be particularly useful, because it can convert a differential, voltage-mode signal into a non-differential, current-mode signal. The aforementioned non-dynamically biased circuit—which can send a signal into the input I_{in} of the envelope detector of FIG. **12**—is not to be confused with the dynamically biased version of the circuit of FIG. **1**, in which the bias current I_E can be adjusted by an output current—e.g., $\gamma_{13}I_{124}$ or $\delta_{13}I_{124}$—of a current mirror receiving the output current αI_{124} of the envelope detector of FIG. **12**.

The envelope detector of FIG. **12** can also be utilized to control the bias of a filter such as the low-pass filters of FIGS. **8a** and **8b**. For example, the input signal i_{in} of the filter of FIG. **8a**—or a signal proportional to i_{in}—can be used as the input signal I_{in} of the envelope detector of FIG.

12. The collector current of one of the output transistors Q_{128} (illustrated in FIGS. **12** and **13**) can then be used as the bias input I_{bias} of the filter of FIG. **8***a*. A matching collector current approximately equal to I_{bias} and produced by, e.g., a different one of the output transistors Q_{128} can similarly be used to bias an auxiliary circuit such as the circuit of FIG. **8***b*.

An envelope detector such as the one illustrated in FIG. **12** can also be used, in conjunction with a current mirror, to provide a bias current $(I_{2p}/I_{3p})I_{bias}$ into the output transistor Q_{4p} of the filter of FIG. **8***a*. In addition, the envelope detector and current mirror can be used to provide a bias current $(I_{2n}/I_{3n})I_{bias}$ into the output transistor Q_{4n} of the filter of FIG. **8***b*.

An example of such a configuration is illustrated in FIG. **16**, in which the envelope detector **1200** of FIG. **12** pulls current from a diode-connected PNP transistor Q_{m1}, the base and collector of which are connected to the respective bases of current-mirror transistors Q_{m2} and Q_{m3}. The emitters of Q_{m1}, Q_{m2}, and Q_{m3} are connected to a voltage source V_{H16}.

Transistor Q_{m1} has a cross-sectional area A_{x1}. Transistor Q_{m2} has an approximately equal cross-sectional area, and therefore produces approximately the same current, $I_{bias}=\alpha I_{124}$, as is pulled through Q_{m1}. However, transistor Q_{m3} is designed to have a cross-sectional area $(I_{2p}/I_{3p})A_{x1}$. Therefore, because the collector current of a bipolar transistor is generally proportional to the area of the transistor, Q_{m3} produces a current $(I_{2p}/I_{3p})I_{bias}$ which can be used to bias transistor Q_{4p} of the filter of FIG. **8***a*. In a preferred embodiment, an additional transistor Q_{m4} having an area $(I_{2n}/I_{3n})A_{x1}$ can be included in the current mirror of FIG. **16**. The resulting current, $(I_{2n}/I_{3n})I_{bias}$, can be used to bias transistor Q_{4n} of the filter of FIG. **8***b*. Moreover, it is desirable to provide yet another transistor Q_{m2}' having an area of approximately A_{x1}, in order to provide bias current for Q_{in} of the filter of FIG. **8***b*.

In accordance with an additional embodiment of the invention, the input (i.e., compressing) stage of a companding filter can be eliminated, leaving only the frequency-dependent components and the expanding stage. An example of such a technique is illustrated by FIGS. **20***a* and **20***b*. FIG. **20***a* is a block diagram of an exemplary log-domain circuit having an input circuit **2002** and an output circuit **2004**. The input circuit receives an input current i_{in20} and performs a logarithmic operation on the input current i_{in20}, thus generating a logarithmically compressed voltage V_{log20}. The output circuit **2004** filters and exponentiates the compressed voltage V_{log20}, thus generating an output current i_{out20}.

In accordance with the invention, the input circuit **2002** can be eliminated, leaving only the output circuit **2004**, as illustrated in FIG. **20***b*. The output circuit **2004** acts as a combination of an exponentiator and a low-pass filter. An input voltage V_{in20} can be applied directly to the input of the circuit **2004** which then generates a filtered, exponentiated output current i_{out20} based upon the input voltage V_{in20}. Such a circuit can be useful for applications requiring an exponential filter. For example, the filter-exponentiator **2004** of FIG. **20** can, optionally, be used to replace the filter **1104** and the exponentiator **1102** of the circuit of FIG. **11**.

It has been demonstrated by the foregoing discussion that the design of syllabic companding log-domain filters can be greatly simplified by eliminating the compensation circuit in accordance with the invention. As discussed in detail above, the approach of the invention has numerous advantages over

conventional methods involving syllabic companding and instantaneous companding log-domain filters.

Although the present invention has been described in connection with specific exemplary embodiments, it should be understood that various changes, substitutions and alterations can be made to the disclosed embodiments without departing from the spirit and scope of the invention as set forth in the appended claims.

What is claimed is:

1. An apparatus for processing a signal, comprising:

a filter having at least one input and at least one bias, wherein the at least one input comprises:

a first input for receiving a first input signal, and

a second input for receiving a second input signal, wherein the filter is configured to perform the steps of:

applying a first filtering operation to the first input signal, thereby generating a first output signal which is communicated to at least one output of the filter, the first filtering operation having a first frequency characteristic in which low frequencies are suppressed, and

applying a second filtering operation to the second input signal, the second input signal controlling the at least one bias, the second filtering operation having a second frequency characteristic in which low frequencies are passed; and

an envelope detector for receiving the first input signal for generating a signal representing an amplitude of the first input signal, the second input signal comprising the signal representing the amplitude of the first input signal.

2. An apparatus as recited in claim **1**, wherein the first frequency characteristic comprises at least one of a band-pass characteristic and a high-pass characteristic, the at least one bias being isolated from low-frequency components of the first input signal.

3. A method of processing a signal, comprising:

receiving a first input signal into a filter having at least one bias;

detecting an envelope of the first input signal for generating a signal representing an amplitude of the first input signal;

receiving a second input signal into the filter, the second input signal comprising the signal representing the amplitude of the first input signal;

using the filter to apply a first filtering operation to the first input signal, thereby generating a first output signal which is communicated to at least one output of the filter, the first filtering operation having a first frequency characteristic in which low frequencies are suppressed; and

using the filter to apply a second filtering operation to the second input signal, the second input signal controlling the at least one bias, the second filtering operation having a second frequency characteristic in which low frequencies are passed.

4. A method as recited in claim **3**, wherein the first frequency characteristic comprises at least one of a band-pass characteristic and a high-pass characteristic, the at least one bias being isolated from low-frequency components of the first input signal.

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