United States Patent [19]

Anderson et al.

[11] **Patent Number: 4,792,977**

[45] **Date of Patent: Dec. 20, 1988**

[54] **HEARING AID CIRCUIT**

[75] Inventors: **James R. Anderson**, Chicago; **Richard Brander**, Cicero, both of Ill.

[73] Assignee: **Beltone Electronics Corporation**, Chicago, Ill.

[21] Appl. No.: **838,924**

[22] Filed: **Mar. 12, 1986**

[51] **Int. Cl.**[4] **H04R 25/00**; H04R 3/04; H03G 3/20; H03G 11/04

[52] **U.S. Cl.** **381/68.4**; 381/68; 381/68.2; 381/104

[58] **Field of Search** 381/68.2, 68.4, 105, 381/106, 68; 333/14

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,927,279	12/1975	Nakamura	381/68.2
4,099,035	7/1978	Yanick	381/68.2
4,119,814	10/1978	Harless	381/68.2
4,354,064	10/1982	Scott	381/68.2
4,366,349	12/1982	Adelman	381/68.2
4,405,831	9/1983	Michelson	381/68.4
4,409,435	10/1983	Ono	381/68.2
4,484,345	11/1984	Stearns	381/68.2
4,490,691	12/1984	Dolby	381/106
4,508,940	4/1985	Steeger	381/68.2
4,517,415	5/1985	Laurence	381/68.4
4,535,471	8/1985	Kuroda	381/106
4,596,902	6/1986	Gilman	381/68.2
4,630,305	12/1986	Borth	381/68.2

OTHER PUBLICATIONS

Authors: F. Callias, F. Salchli, D. Girard, M. Perrin & Ph. Aubert Title: A Set of 4 IC's In CMOS Technology for a Programmable Hearing Aid; published in the IEEE 1988 Custom Integrated Circuits Conference, May, 1988.

Solid State Microtechnology for Music data sheet, entitled "Dual Linear-Antilog Voltage Controlled Amplifier" by Solid State Micro Technology for Music, Inc. (1 page).

Article entitled "Coming To Terms With Hearing Aid Technology" by Preben Brunved, published in the Hearing Journal, Jun., 1985 (5 pages).

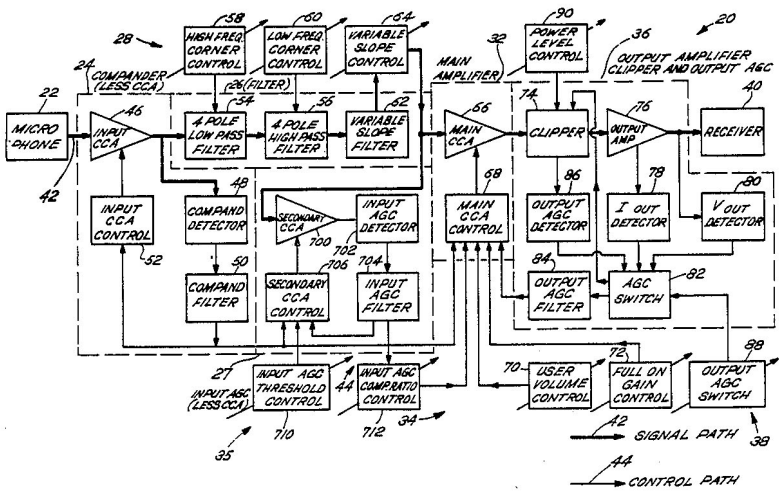
LTI data sheet, entitled "Dual Continuous Analog High Pass Filter" by LTI, bearing designation 500-73-1 (4 pages).

Primary Examiner—Jin F. Ng
Assistant Examiner—Danita R. Byrd
Attorney, Agent, or Firm—Allegretti & Witcoff, Ltd.

[57] **ABSTRACT**

A hearing aid that is compact and efficient and that provides a high degree of control over its frequency response and also over its output level versus input level characteristic. The frequency response control includes an adjustable four pole high pass filter and an adjustable four pole low pass filter, to define the pass band, and an adjustable slope filter, to define the slope within the pass band. The control over the output level versus input level characteristic includes an input AGC system with well defined, independent control of compression threshold and compression ratio, an adjustable peak clipper, and a selectable output AGC system that tracks the peak clipper setting. The hearing aid incorporates a number of novel circuits including a state variable filter with adjustable corner frequency, a filter that can be continuously adjusted from a single pole low pass characteristic to a single pole high pass characteristic, a circuit to provide a range of reference voltages to accurately set the range of control currents used to control the corner frequencies of the state variable filters, a compansion system surrounding the filter network to effectively increase its limited dynamic range, a differential voltage threshold detector, a differential voltage controlled current source with an exponential relationship of output current to differential input voltage, an adjustable clipping circuit, a voltage clamp to prevent voltage excursions from going substantially below a substrate voltage, and bias compensation circuit to supply the input bias current of a transistor.

13 Claims, 16 Drawing Sheets



Bose Exhibit 1028
Bose v. IngenioSpec

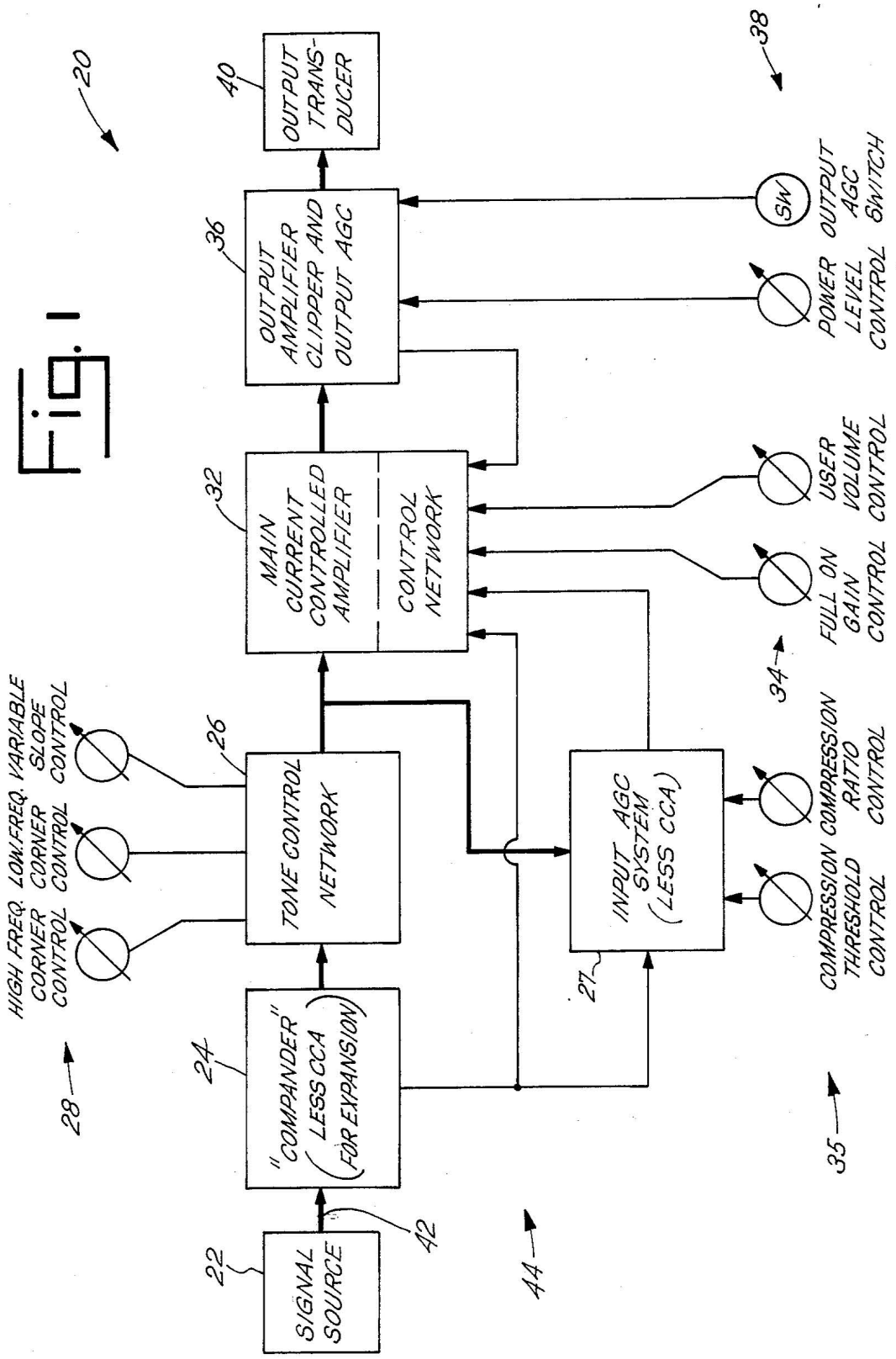

20
22
SIGNAL SOURCE
24
"COMPANDER" (LESS CCA FOR EXPANSION)
26
TONE CONTROL NETWORK
27
INPUT AGC SYSTEM (LESS CCA)
28
HIGH FREQ. CORNER CONTROL
LOW FREQ. CORNER CONTROL
VARIABLE SLOPE CONTROL
32
MAIN CURRENT CONTROLLED AMPLIFIER
CONTROL NETWORK
34
FULL ON GAIN CONTROL
USER VOLUME CONTROL
35
COMPRESSION THRESHOLD CONTROL
COMPRESSION RATIO CONTROL
36
OUTPUT AMPLIFIER CLIPPER AND OUTPUT AGC
38
POWER LEVEL CONTROL
SW
OUTPUT AGC SWITCH
40
OUTPUT TRANS-DUCER
42
44

Fig. 1

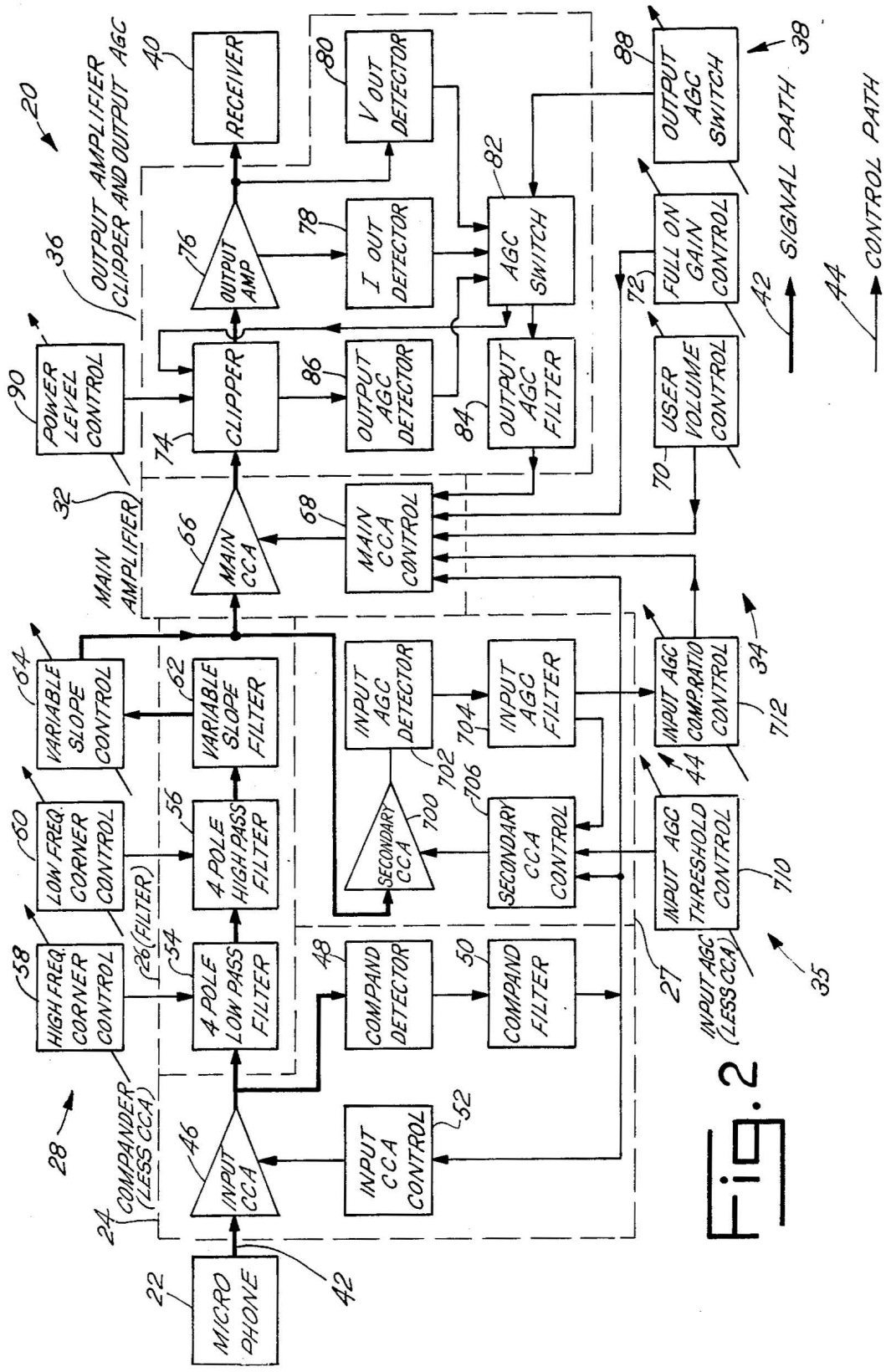

20
OUTPUT AMPLIFIER CLIPPER AND OUTPUT AGC
36
RECEIVER
40
V OUT DETECTOR
80
OUTPUT AGC SWITCH
88
38
SIGNAL PATH
42
CONTROL PATH
44
OUTPUT AMP
76
I OUT DETECTOR
78
AGC SWITCH
82
FULL ON GAIN CONTROL
72
POWER LEVEL CONTROL
90
CLIPPER
74
OUTPUT AGC DETECTOR
86
OUTPUT AGC FILTER
84
USER VOLUME CONTROL
70
32
MAIN AMPLIFIER
MAIN CCA
66
MAIN CCA CONTROL
68
VARIABLE SLOPE CONTROL
64
VARIABLE SLOPE FILTER
62
INPUT AGC DETECTOR
702
INPUT AGC FILTER
704
INPUT AGC COMP.RATIO CONTROL
712
34
LOW FREQ. CORNER CONTROL
60
4 POLE HIGH PASS FILTER
56
SECONDARY CCA
700
SECONDARY CCA CONTROL
706
INPUT AGC THRESHOLD CONTROL
710
44
HIGH FREQ. CORNER CONTROL
58
(FILTER)
26
4 POLE LOW PASS FILTER
54
COMPAND DETECTOR
48
COMPAND FILTER
50
27
35
INPUT AGC (LESS CCA)
28
COMPANDER (LESS CCA)
24
INPUT CCA
46
INPUT CCA CONTROL
52
MICRO PHONE
22
42

Fig. 2

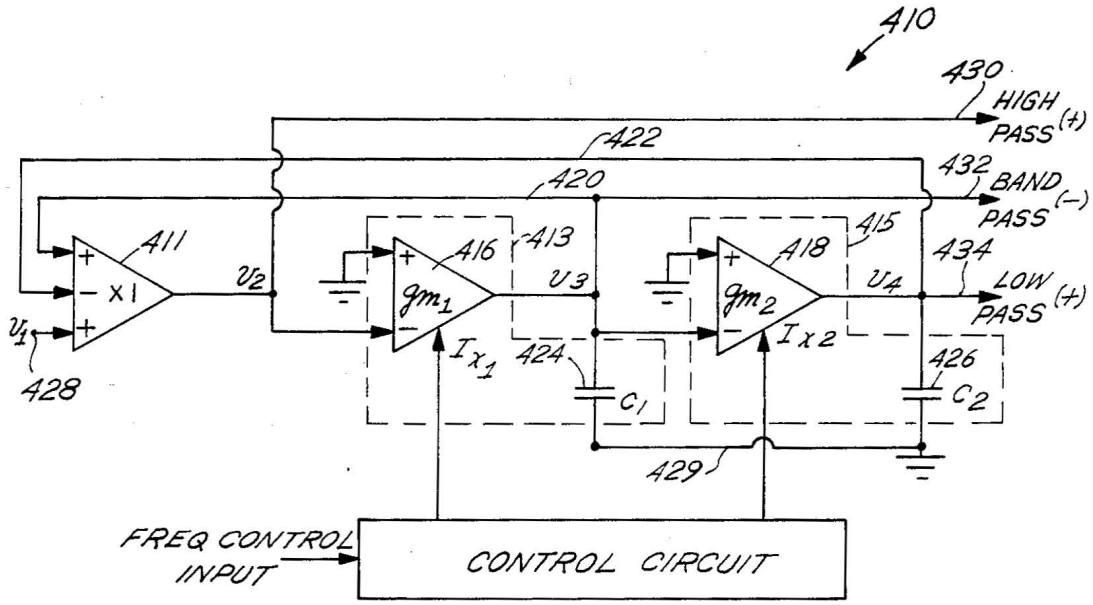

410
430
HIGH PASS (+)
422
420
432
BAND PASS (−)
411
413
415
434
LOW PASS (+)
416
418
V_2
V_3
V_4
V_1
428
gm_1
gm_2
I_{x_1}
I_{x_2}
424
426
C_1
C_2
429
FREQ CONTROL INPUT
CONTROL CIRCUIT

Fig. 3

Fig. 4

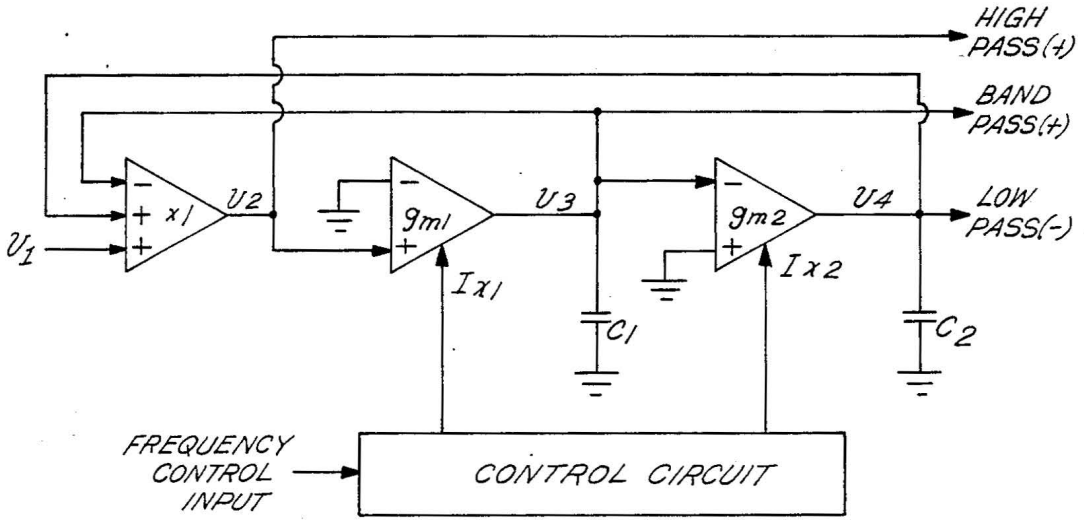
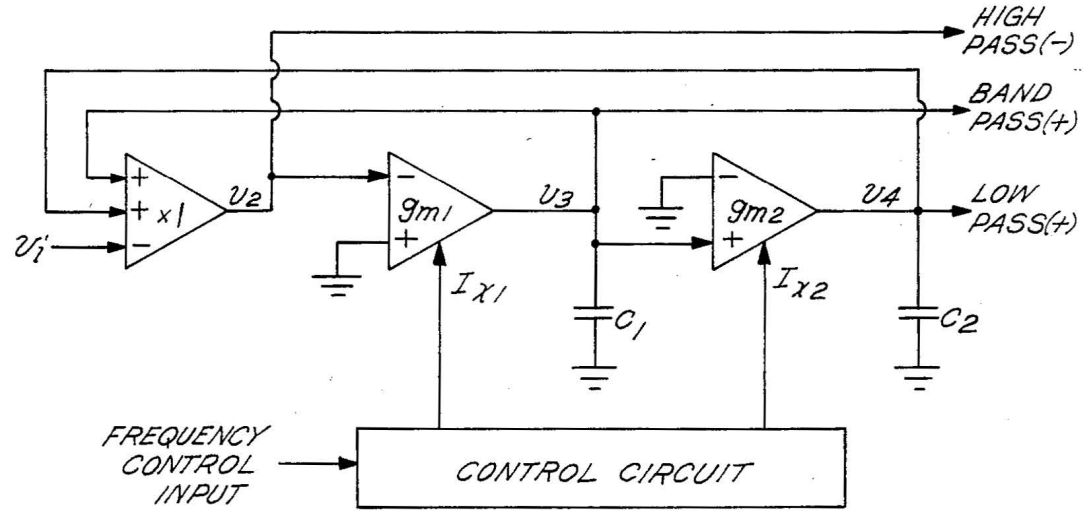

HIGH PASS(+)
BAND PASS(+)
LOW PASS(-)
x1
gm1
gm2
V1
V2
V3
V4
Ix1
Ix2
C1
C2
FREQUENCY CONTROL INPUT
CONTROL CIRCUIT

Fig. 5


HIGH PASS(-)
BAND PASS(+)
LOW PASS(+)
x1
gm1
gm2
Vi
V2
V3
V4
Ix1
Ix2
C1
C2
FREQUENCY CONTROL INPUT
CONTROL CIRCUIT

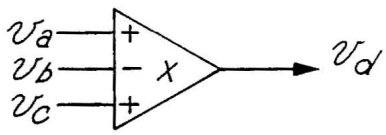


Fig. 6

Fig. 7

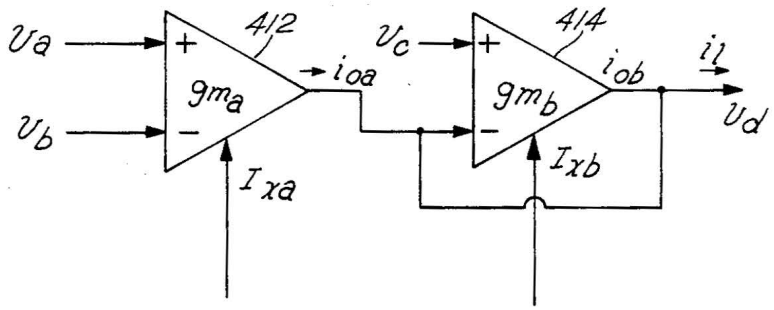


Fig. 8

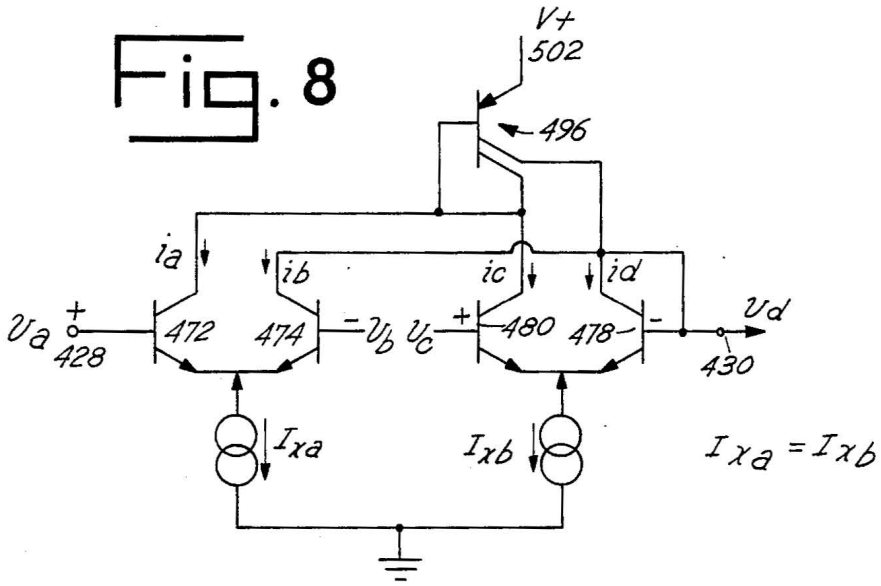


Fig. 9

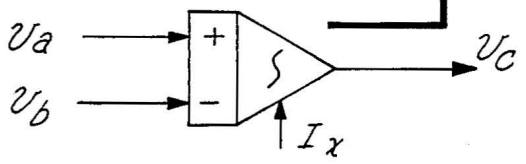


Fig. 10

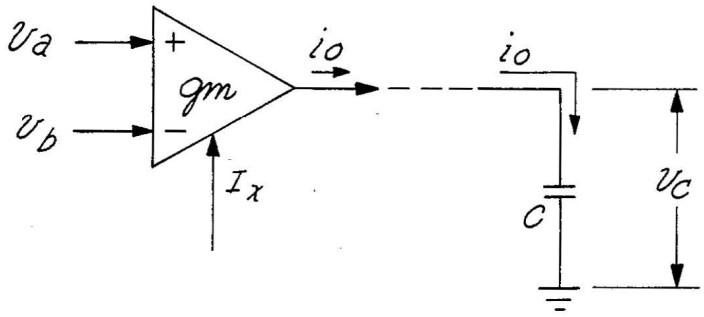


Fig. 11

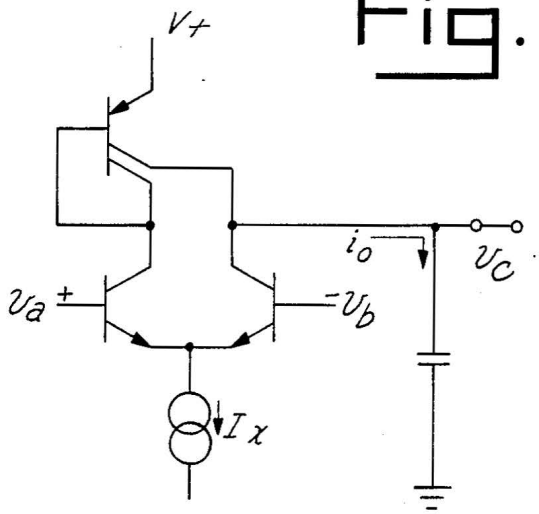


Fig. 12

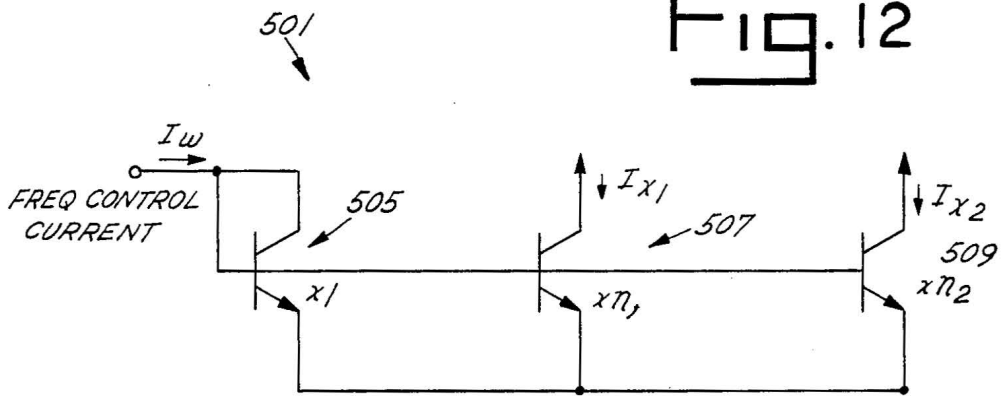


Fig. 12a

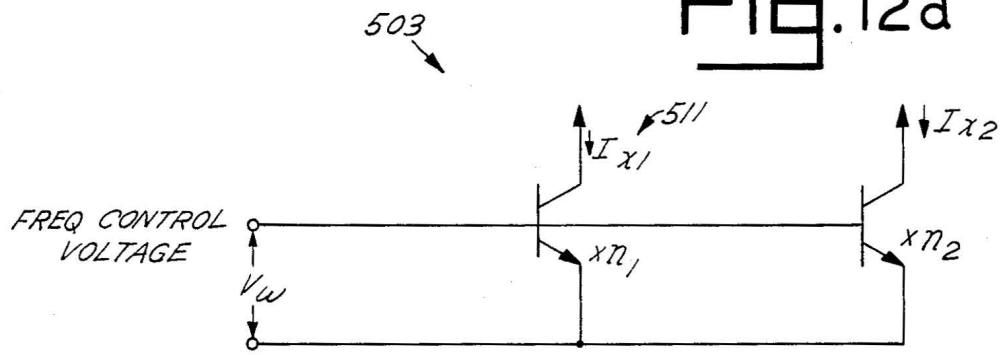


Fig. 13

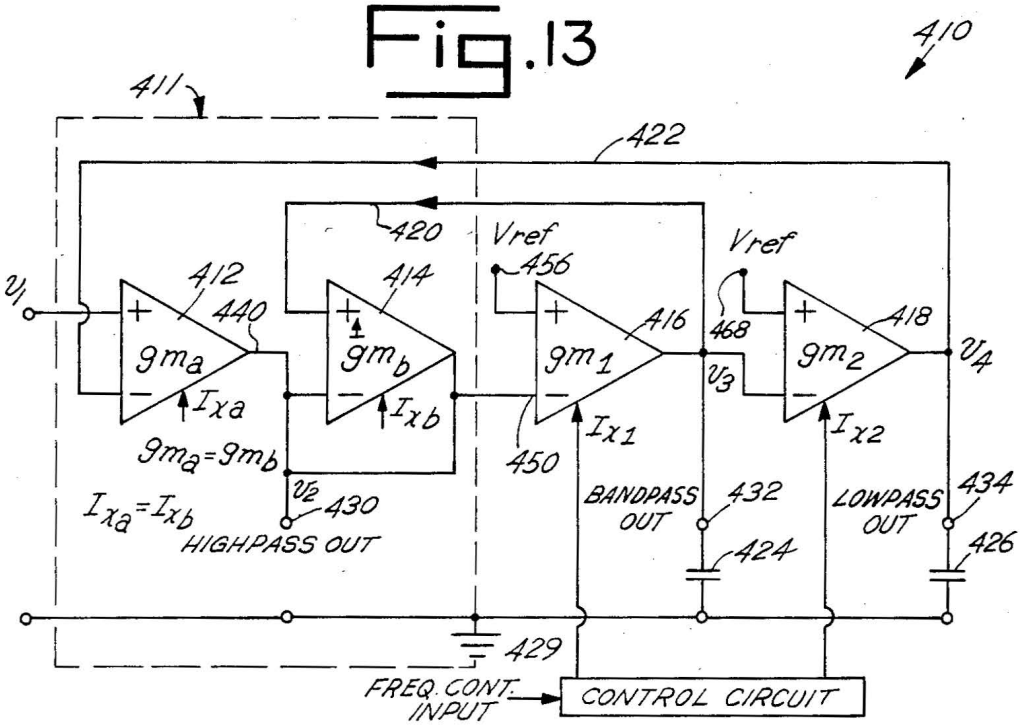

410
411
422
420
Vref
456
Vref
468
412
414
416
418
440
V_I
g_{ma}
g_{mb}
g_{m1}
g_{m2}
V_4
V_3
I_{xa}
I_{xb}
I_{x1}
I_{x2}
$g_{ma}=g_{mb}$
450
$I_{xa}=I_{xb}$
V_2 430
HIGHPASS OUT
BANDPASS OUT
432
LOWPASS OUT
434
424
426
429
FREQ. CONT. INPUT
CONTROL CIRCUIT

Fig. 14

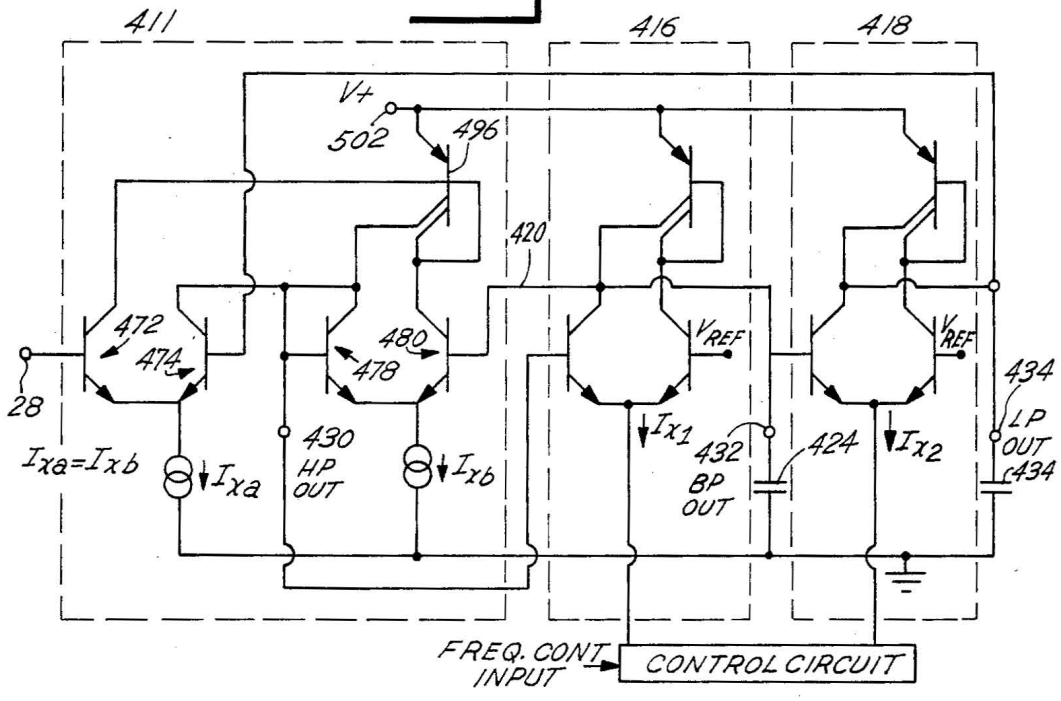

411
416
418
V+
502
496
420
472
474
480
478
V_{REF}
V_{REF}
28
434
LP OUT
434
$I_{xa}=I_{xb}$
I_{xa}
430
HP OUT
I_{xb}
I_{x1}
432
BP OUT
424
I_{x2}
FREQ. CONT. INPUT
CONTROL CIRCUIT

Fig. 15

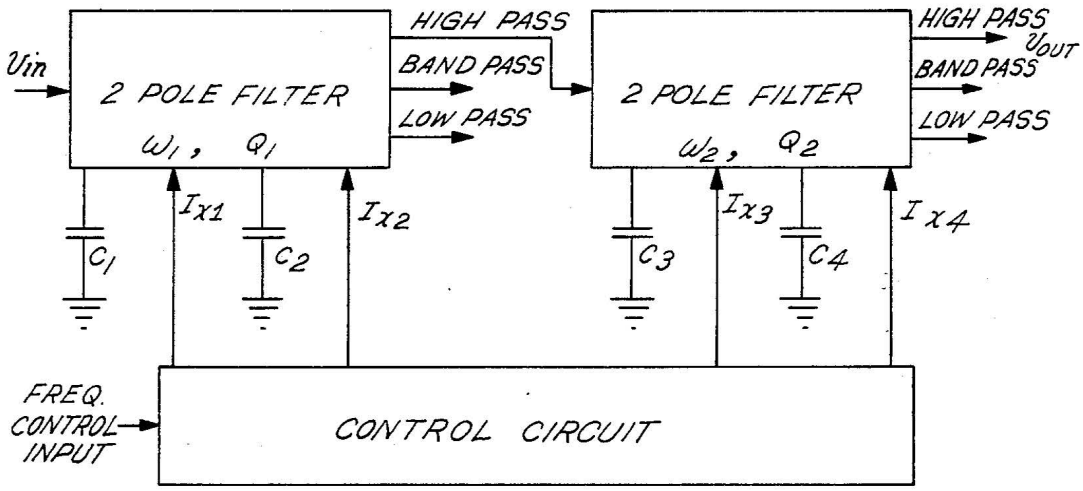

Vin
2 POLE FILTER
ω1, Q1
HIGH PASS
BAND PASS
LOW PASS
2 POLE FILTER
ω2, Q2
HIGH PASS
VOUT
BAND PASS
LOW PASS
Ix1
Ix2
Ix3
Ix4
C1
C2
C3
C4
FREQ. CONTROL INPUT
CONTROL CIRCUIT

Fig. 16

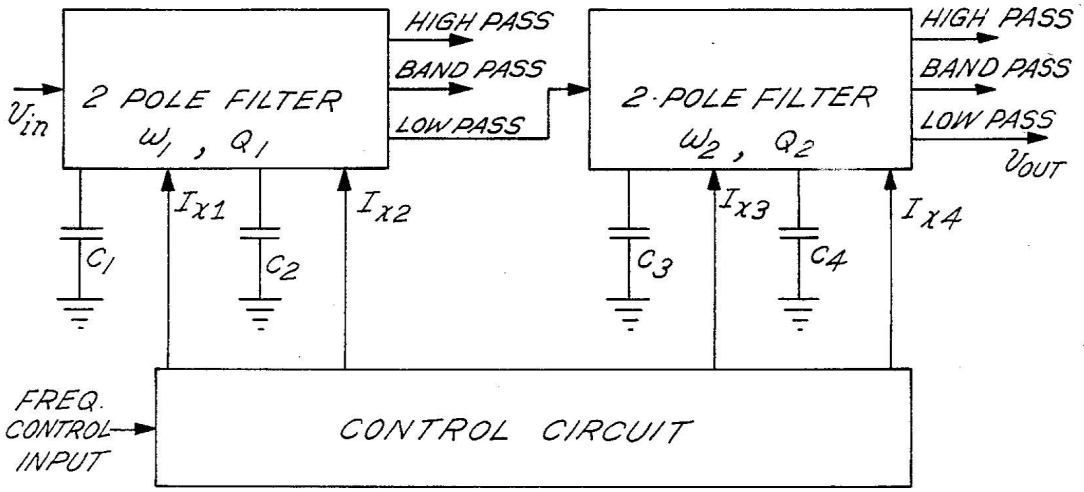

Vin
2 POLE FILTER
ω1, Q1
HIGH PASS
BAND PASS
LOW PASS
2 POLE FILTER
ω2, Q2
HIGH PASS
BAND PASS
LOW PASS
VOUT
Ix1
Ix2
Ix3
Ix4
C1
C2
C3
C4
FREQ. CONTROL INPUT
CONTROL CIRCUIT

Fig. 17

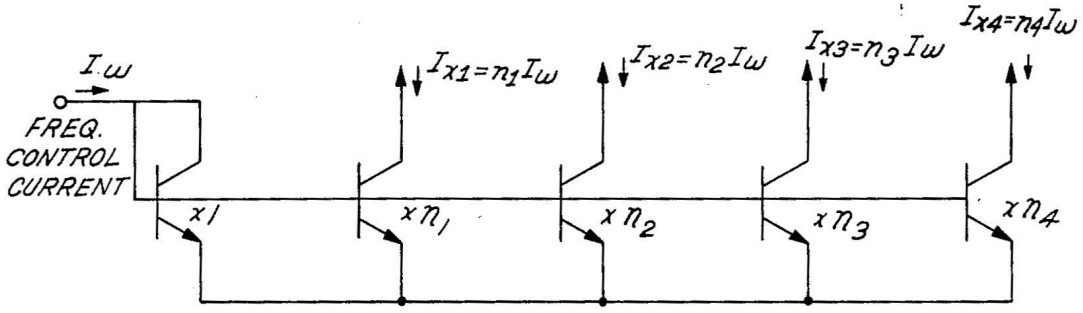

$I_{x4}=n_4 I_\omega$
I_ω
$I_{x1}=n_1 I_\omega$
$I_{x2}=n_2 I_\omega$
$I_{x3}=n_3 I_\omega$
FREQ. CONTROL CURRENT
x1
$x n_1$
$x n_2$
$x n_3$
$x n_4$

Fig. 18

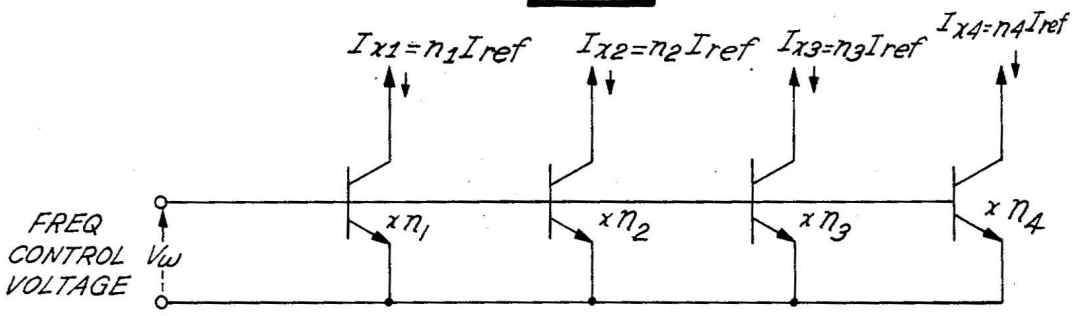

$I_{x1}=n_1 I_{ref}$
$I_{x2}=n_2 I_{ref}$
$I_{x3}=n_3 I_{ref}$
$I_{x4}=n_4 I_{ref}$
FREQ CONTROL VOLTAGE
V_ω
$x n_1$
$x n_2$
$x n_3$
$x n_4$

Fig. 19

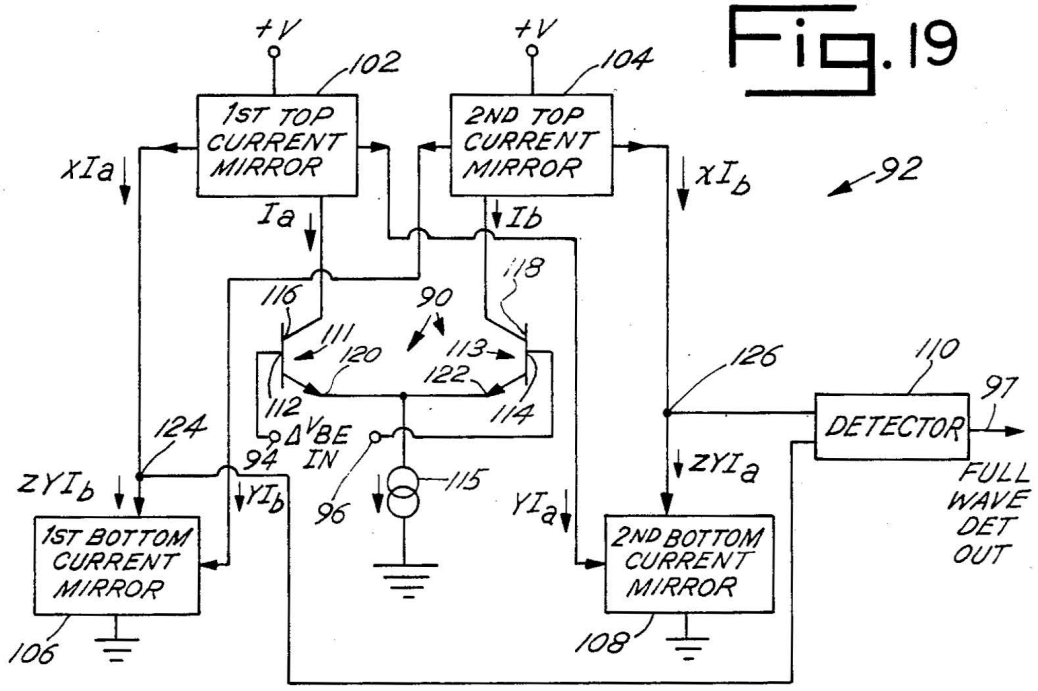

+V
+V
102
104
1ST TOP CURRENT MIRROR
2ND TOP CURRENT MIRROR
xIa
xIb
92
Ia
Ib
116
118
90
111
113
120
122
126
110
97
112
114
124
94
ΔVBE IN
96
115
zYIb
YIb
YIa
zYIa
DETECTOR
FULL WAVE DET OUT
1ST BOTTOM CURRENT MIRROR
2ND BOTTOM CURRENT MIRROR
106
108

Fig. 21

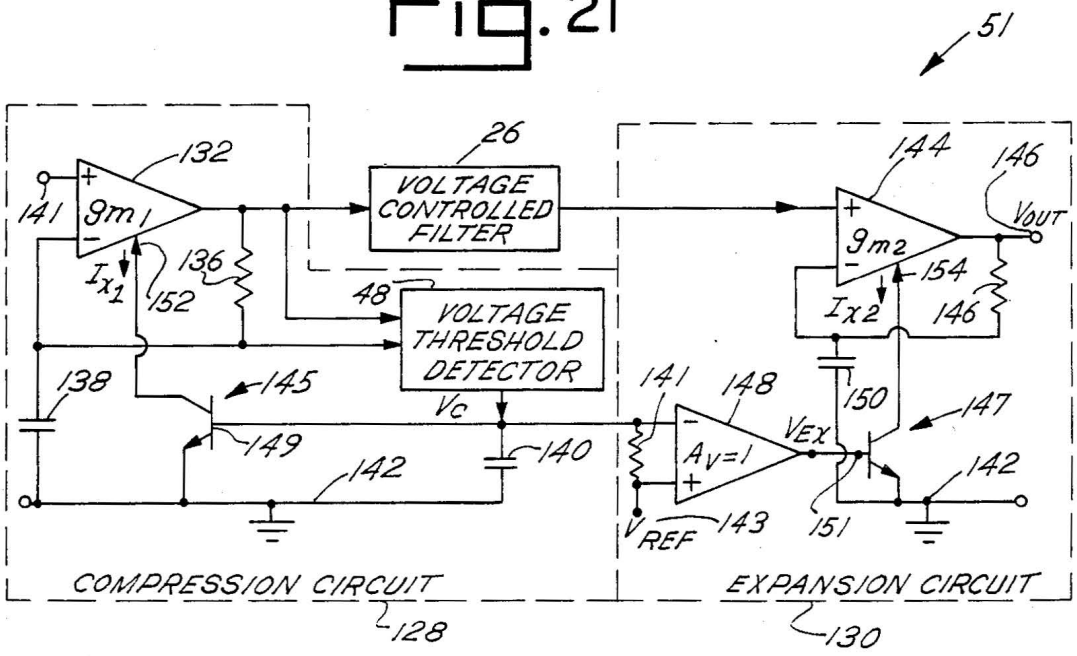

51
26
132
144
146
141
9m1
VOLTAGE CONTROLLED FILTER
9m2
VOUT
Ix1
152
136
48
154
Ix2
146
VOLTAGE THRESHOLD DETECTOR
138
145
141
148
150
147
Vc
VEX
149
140
AV=1
142
142
VREF
143
151
COMPRESSION CIRCUIT
128
EXPANSION CIRCUIT
130

Fig. 20

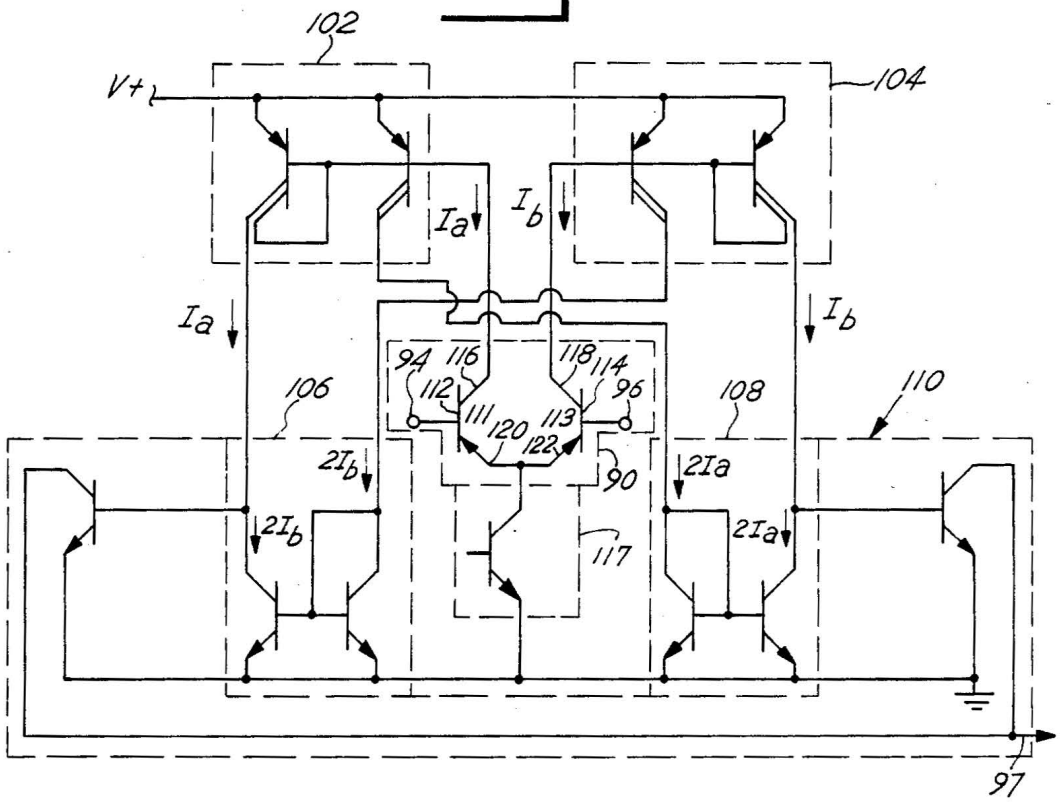

102
104
V+
Ia
Ib
Ia
Ib
94
116
118
114
112
96
111
120
113
122
106
108
110
2Ib
90
2Ia
2Ib
117
2Ia
97

Fig. 22

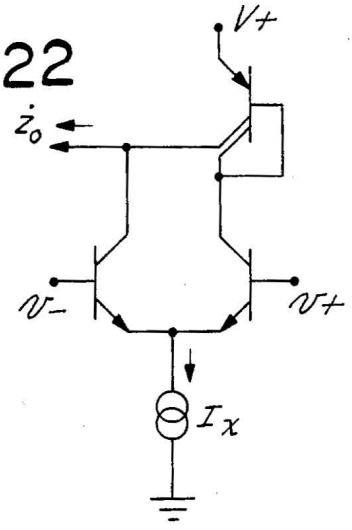

V+
i_o
V−
V+
I_x

Fig. 23

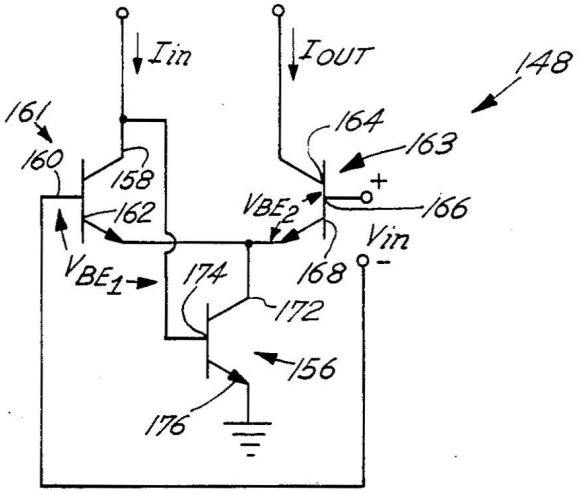


Fig. 24a

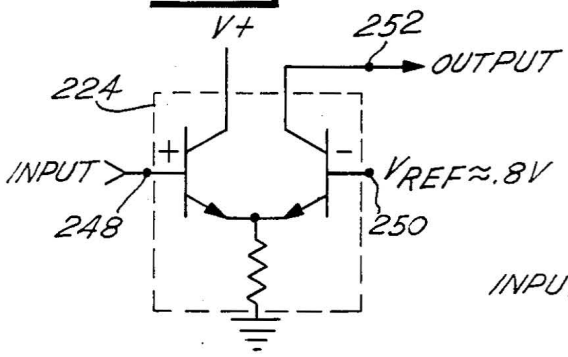


Fig. 24b

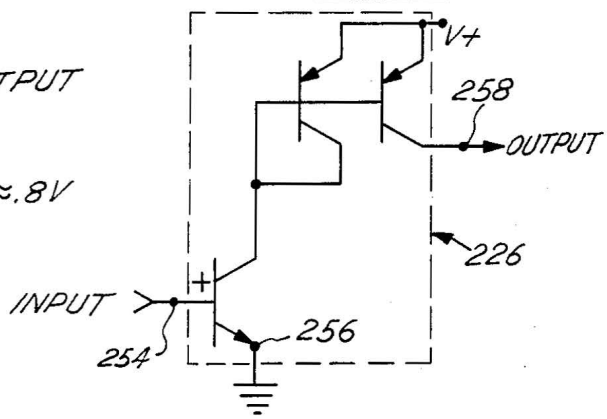


Fig. 25

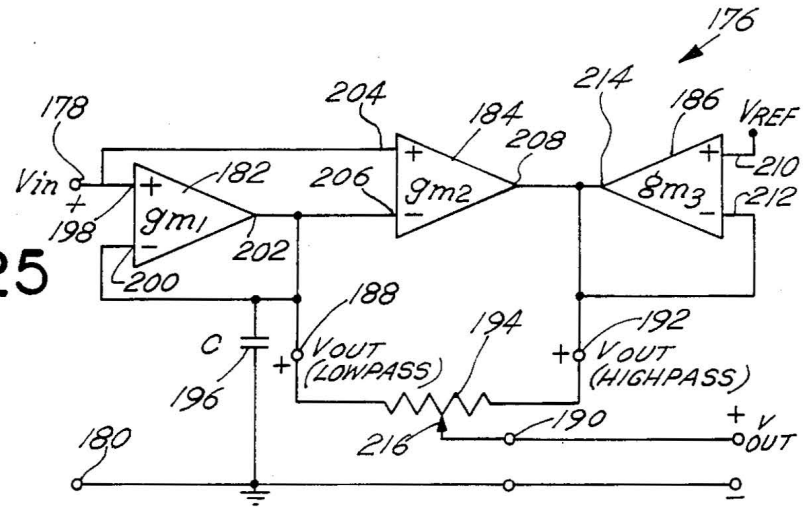


Fig. 24

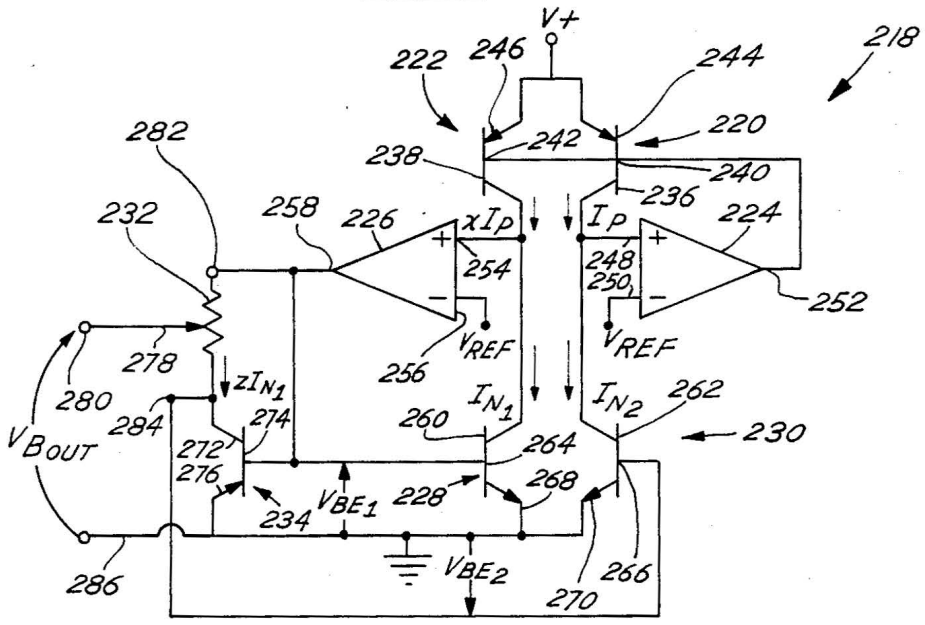

V+
218
222
246
244
220
242
238
240
236
224
232
282
258
226
xIp
Ip
254
248
250
252
256
VREF
VREF
278
280
284
zIN1
IN1
IN2
262
260
264
230
VBOUT
272
274
276
234
VBE1
228
268
VBE2
266
270
286

Fig.26

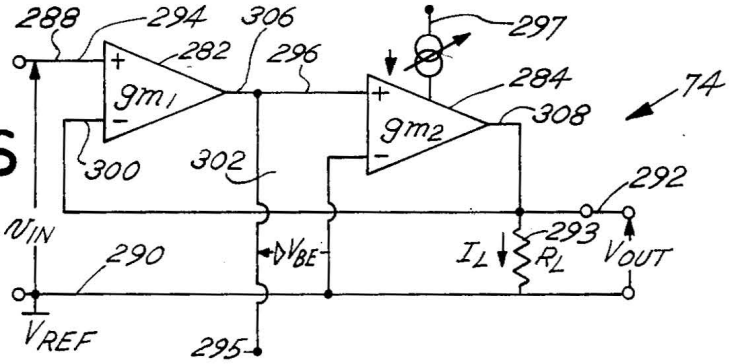


Fig.27

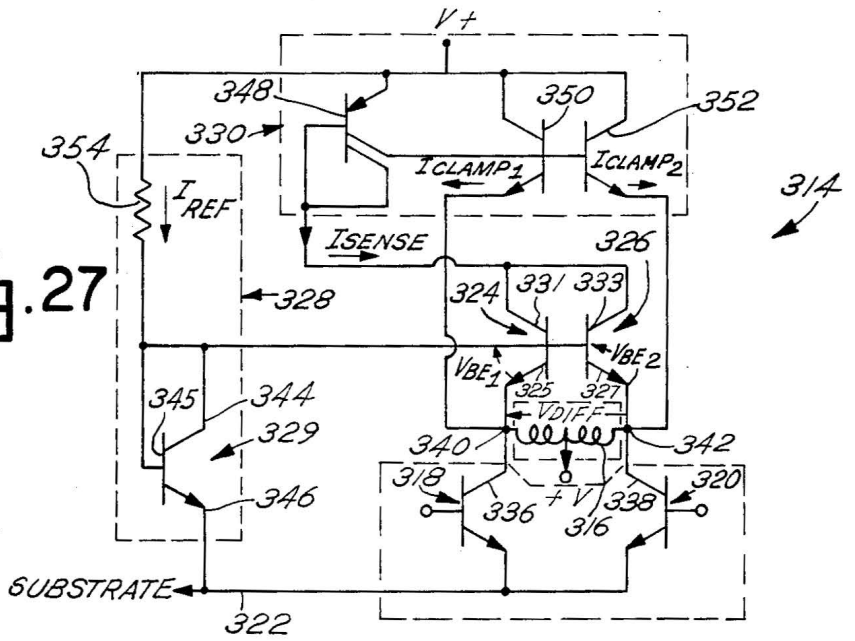


Fig.28

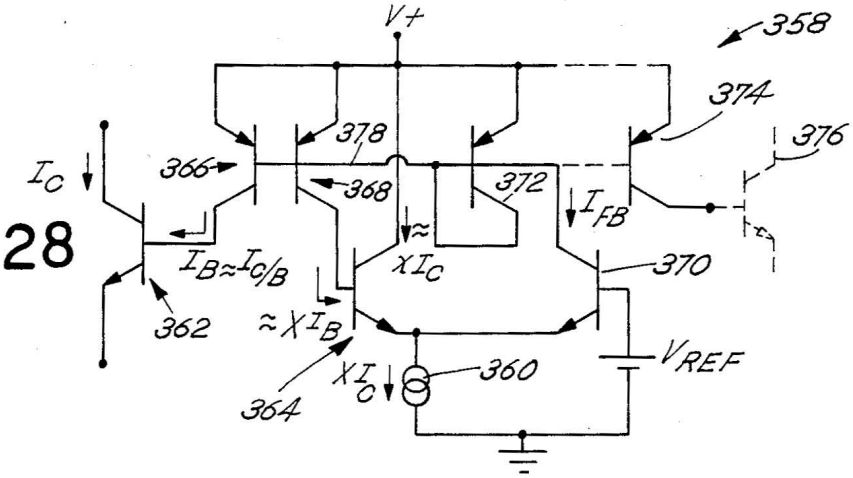


Fig. 29

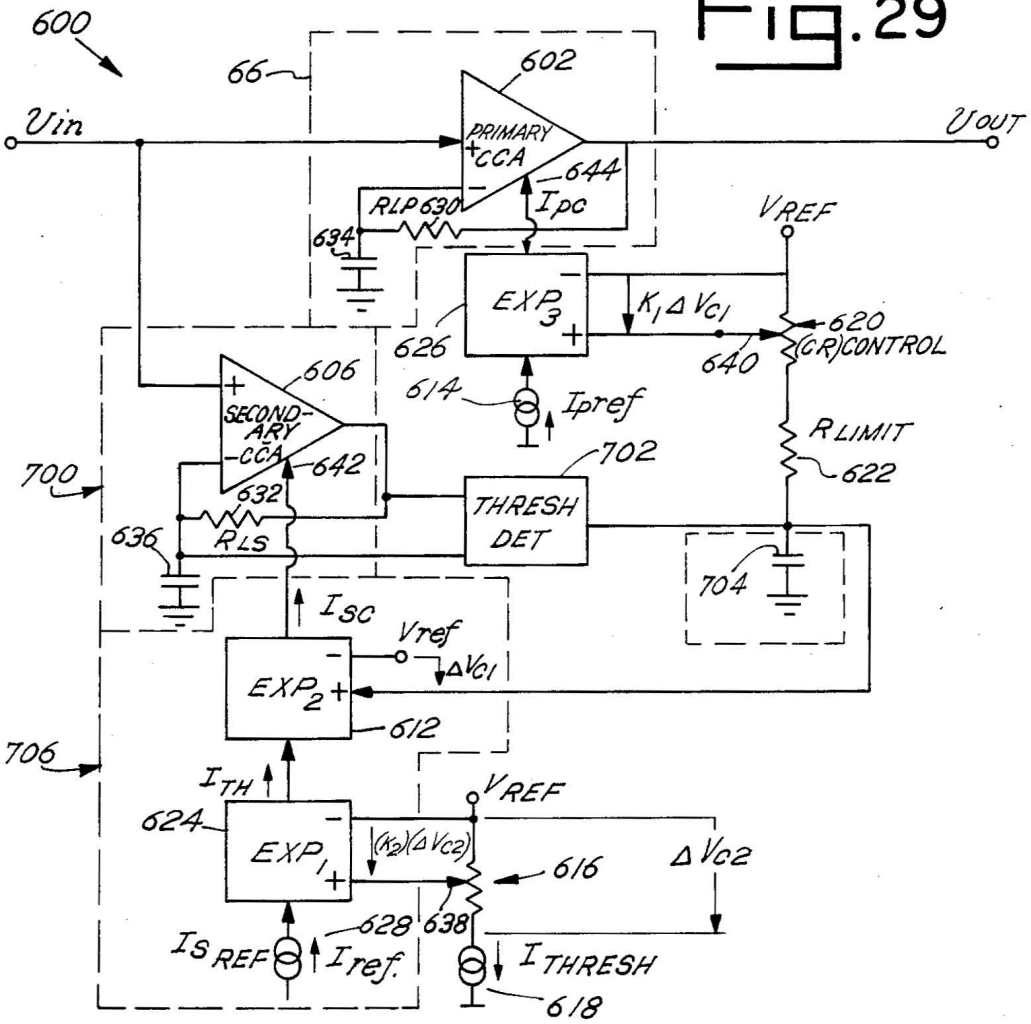
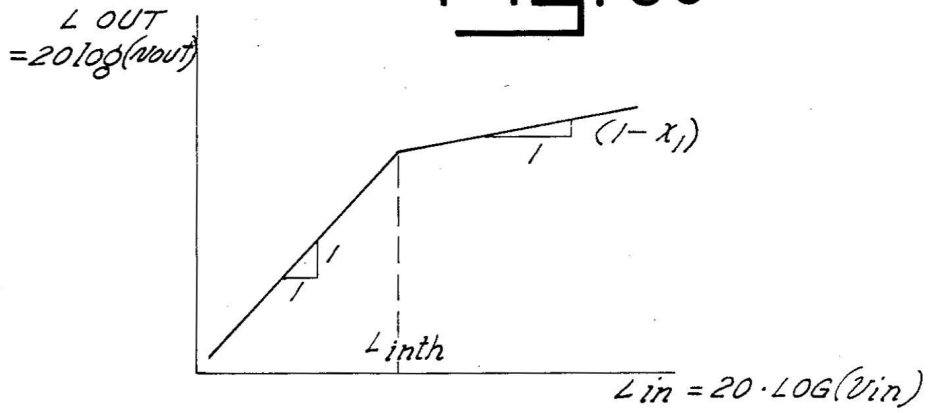

600
66
602
Vin
PRIMARY CCA
644
Vout
RLP 630
Ipc
634
VREF
EXP3
K1 ΔVc1
620
(G.R) CONTROL
626
640
606
614
Ipref
SECOND-ARY -CCA
642
RLIMIT
622
700
632
702
THRESH DET
636
RLS
704
Isc
Vref
ΔVc1
EXP2
612
706
ITH
VREF
624
EXP1
(K2)(ΔVc2)
616
ΔVc2
628
638
IS REF
Iref.
ITHRESH
618

Fig. 30


L OUT
=20log(vout)
(1-x1)
1
1
1
Linth
Lin = 20·LOG(Vin)

HEARING AID CIRCUIT

BACKGROUND OF THE INVENTION

The present invention relates generally to hearing aids, and more particularly, to circuits that more compactly, economically, and effectively present a modified and amplified sound for the wearer of a hearing aid. In its most basic form, a hearing aid is a device which receives a sound signal and furnishes a modified sound signal to the wearer of the hearing aid, so that the wearer may hear better.

Hearing impaired persons differ considerably in the degree and pattern of their hearing loss. This is reflected in their audiograms.

An audiogram is a chart of hearing threshold level (HTL) versus frequency. The HTL is measured on a logarithmic (decibel) scale and compares an individual's threshold of detection of a tone to that of normal hearing persons.

Audiograms can differ in level from near normal (0 dB HTL) to profound loss (greater than 100 dB HTL). They can vary in pattern from a flat audiogram (approximately equal HTL over the relevant frequency range) to a sharply falling audiogram (HTL increasing at more than 30 dB per octave of frequency increase) or to a rising audiogram (HTL decreasing with frequency). Within the category of sharply falling audiograms, the frequency at which the audiogram begins to fall can vary greatly between individuals.

Patterns of hearing loss can also differ considerably in the relationship between the subjectively experienced loudness and the input sound pressure level. Not only are there wide differences in the lowest level that the ear can perceive (the HTL), there are also wide differences in the highest level that the ear can tolerate (the loudness discomfort level or LDL) and differences in the rate of growth of loudness between these two extremes. In some cases, a much higher than normal HTL is combined with a lower than normal LDL, giving a much reduced dynamic range of usable sound levels.

Because of the large differences in degree and pattern of hearing loss, there is also a wide range of hearing aid characteristics required to optimally assist hearing impaired persons. The frequency response of the hearing aid must be selected for the individual hearing loss and may require high order filtering with selection of frequency bandwidth as well as general shape within that bandwidth. The gain of the hearing aid must be selected in accordance with the degree of the hearing loss.

The limiting level of the hearing aid must be selected in accordance with the LDL. A selection of the type of output limiting must be made between peak clipping, or output Automatic Gain Control ("AGC"). Output AGC is an automatic gain control system whose action is related to the output level of the hearing aid. This relation is substantially independent of the setting of the user operated volume control.

If the ear has a much reduced dynamic range, an input AGC system may be needed. Input AGC is an automatic gain control system whose action is related to the input level to the hearing aid. The relation between the action of the input AGC and the input level is also substantially independent of the setting of the user-operated volume control. In the case of an input AGC, a selection must be made of the compression threshold, (the input level at which AGC action begins), and the compression ratio, (the ratio of the decibel change in input to the decibel change in output level).

It is desirable that a single hearing aid be provided with a range of adjustability in these various characteristics. This is important not only because it allows a single hearing aid model to be used for many persons with differing hearing losses, but also because it allows the hearing aid to be readjusted if the initial selection of hearing aid characteristics was incorrect or if the user's hearing loss changes with time.

Because hearing aids are normally worn on the head, they must be small and usually operate with a small single cell battery for extended periods of time. They must also provide good performance, be highly reliable, and be low in cost. The electronic circuits used to provide the various functions of a hearing aid must also have these same characteristics. Of course, such circuits will also be useful in applications other than hearing aids but having similar requirements.

Prior hearing aids have had limitations in meeting the needs described above. They have been limited in the degree of filtering provided to control the frequency response. When equipped with an input AGC system, they have not provided a well-defined compression threshold and a well defined compression ratio. Also, they have not provided the needed degree of adjustability in either their frequency response characteristics or in their output level versus input level and AGC characteristics.

Prior electronic circuits also have had limitations in meeting the needs described above. Circuits that are small in size and that can operate with a low supply voltage of about 1.3 volts and that draw little supply current have not provided good performance and have not provided the desired adjustment characteristics. Prior electronic circuits that could meet the performance needs described above have required higher supply voltage and current, have required many components, have been large in size, or have not been in a form in which they could be adjusted by operation of a single control.

The subsystems, or specific circuits, which help achieve the general objectives for hearing aids have their own specialized goals. Such specific goals are discussed in more detail below.

SPECIFIC SUBSYSTEMS

Filters

In many electronic circuit design applications, such as hearing aids, an input signal is provided. The input signal must then be modified by an appropriate filter. These modifications consist of attenuating the various frequency components of the input signal to differing degrees.

Thus, for example, a hearing aid wearer may have a more serious hearing impairment for sounds having a high frequency than for sounds having a low frequency. Accordingly, a hearing aid should amplify high frequency signals more strongly than the low frequency signals. An appropriate filter may then be used to allow high frequency signals to pass through it substantially unaltered and to substantially attenuate low frequency signals.

In the example described above, the filter is called a highpass filter, since high frequency signals are allowed to pass through the filter substantially unmodified. In addition, a lowpass filter allows only low frequency signals to pass through substantially unattenuated. Still

others, known as bandpass filters, only allow signals having frequencies within a specified range to pass through the filter substantially unattenuated.

In designing a hearing aid, it is desirable to use a more effective and yet compact frequency response filter. Frequency responsive filters are commonly shown in the prior art. For highpass or lowpass filters, a predetermined frequency, known as the corner frequency or characteristic frequency of the filter, substantially divides those signals which are allowed to pass through the filter and those which are attenuated. One type of electronic frequency filter employed in a variety of applications is called a Butterworth filter. For example, in a lowpass Butterworth filter, signals having a frequency less than the corner frequency are allowed to pass through the filter substantially unimpaired. A signal with the frequency of the corner, however, is attenuated by approximately three decibles. Signals with a frequency in excess of the corner frequency are attenuated even more than three decibels.

Filters are further characterized by their number of poles. A pole is a complex frequency root of the denominator of the transfer function. The higher the number of poles, the higher will be the rate of attenuation of a Butterworth filter beyond the corner frequency. For example, a two pole highpass or lowpass filter will have a rate of attenuation of 12 decibels per octave and a four pole filter will have a rate of 24 decibels per octave. In many applications it is desirable to have a four pole filter.

Many applications require filters to be as compact and efficient as possible. For example, hearing aids often rest behind or inside the user's ear. Because of the resulting space limitations, all circuits within the hearing aid, including the frequency filter, should be small. Accordingly, the number of components in each circuit should be reduced.

Also, many applications require that the corner frequency of the filter be adjustable. For example, in hearing aids, users that require amplification of different frequencies may use the same hearing aid simply by adjusting the corner frequency of the filter. A user requiring amplification of signals with a frequency above 500 hertz and another second user, needing amplification of signals above 1000 hertz, may both use the same aid by adjusting the corner frequency of the filter, which determines the frequency response of the aid. Nonetheless, such an adjustable filter should still be as compact as possible.

In addition, the varying of the corner frequency of the filter should, if possible, use only a single control. This allows the adjustment of the corner frequency to be done more easily, as well as allowing the manufacture of the aid to be less expensive and providing a more reliable aid.

Furthermore, since a manually adjusted control element is often mounted in a location remote from the filter circuit, it is advantageous if the input signal does not pass through this control element, but rather that the control element varies a control signal which indirectly influences the corner frequency of the filter. Such an arrangement reduces difficulties that may be encountered with feedback, capacitive coupling, or the pickup of unwanted noise, which will affect the actual signal. Moreover, the control signal may be provided by a manually adjusted potentiometer or may be a signal originating with some other processing system within the aid itself. The control signal should be derived from a regulator that produces reference signals that accurately set the adjustment range of the corner frequency control.

In addition, to further decrease the size of the circuit, a large portion of the circuit should be formed on integrated circuits. In many cases, it is desirable to use semi-custom integrated circuits which contain large numbers of substantially identical circuit elements which may be interconnected as desired. Accordingly, the circuit should advantageously use greater numbers of integer multiples of such identical transistors in its design. Also, such integer multiples of substantially identical transistors may be used to increase the accuracy of the expected performance of the circuit.

Many circuit components used in hearing aids are formed on an integrated circuit chip. Transistors and amplifiers are readily available on such chips and usually do not take up inordinate amounts of space. Resistance elements, however, take up large amounts of space (or "real estate") on the chip. Moreover, the absolute value of a resistor formed on a chip is typically not easily kept within a close tolerance. Such typically wide tolerances would make the circuit performance less accurate. External discrete resistors interconnected with the chip may also be used, but such discrete components also use up much of the space available inside of an aid and also require additional connection points to the chip.

Other elements used in a circuit, such as capacitors, are difficult to fabricate on a chip. Of course, if discrete capacitors are used, they, like discrete resistors, take up space inside the aid, so that their number and size should be minimized. Also, the number of connection points to the chip should be minimized.

It is also helpful if the capacitors used have substantially equal values. In this way, the manufacturer need keep fewer items in inventory. Also, he may purchase larger quantities of the single type of capacitor (rather than smaller quantities of different types of capacitors), and thus possibly obtain the capacitors for a lower price. Consequently, the costs for both the manufacturer and consumer may be reduced. Moreover, the use of a single type of capacitor reduces the chance of "mixup," whereby an improper capacitor is used in the manufacture of the aid.

In addition, it is often desirable to have a common AC ground connection to one side of each capacitor. Such an arrangement tends to reduce the noise sensitivity of the circuit. Moreover, the circuit may then have fewer pad connections between capacitors and the integrated circuit, thereby reducing the cost and increasing the reliability of the circuit.

Of course, the filters should function properly with the voltage level supplied by a hearing aid battery, which is typically in the order of only one volt. Additionally, the filter shall operate with a small current drain, so as to increase the operating life of the battery.

Many commonly available filters only provide a highpass or lowpass or bandpass transfer function, rather than the providing simultaneous highpass, lowpass, and bandpass outputs for a particular input signal. Simultaneous outputs are useful, for example, to split an input signal into highpass and lowpass channels.

Input AGC

In many applications, such as hearing aids, it is desirable that a signal amplification or signal transmission system provide a lower gain for high level input signals than for low input signals. With such an arrangement, a

large range of input signal levels can be transformed into a smaller range of output signal levels.

Such an automatic gain control system ideally is described by a compression threshold and a compression ratio. For input signals below the compression threshold, the signal gain is constant and there is no gain reduction. At the compression threshold, gain reduction begins, and, for signal levels increasing above the compression threshold, the gain is progressively reduced. As a result, the rate of change of output level is smaller than the rate of change of input level. The compression ratio relates to signal levels above the compression threshold and is the ratio of the decibel change in output level to the decibel change in output level. Often it is desirable to provide independent adjustment of compression threshold and compression ratio in order to accommodate different types of inut signals or different needs of users of the output signal.

In an automatic gain control system, it is often important that the gain be changed smoothly without spurious response. Such a spurious response can occur, for example, if the control signal used to adjust an amplifier gain produces a shift or temporary offset in the amplifier output operating current or voltage at the same time as it is changing amplifier gain. This type of spurious response can be heard as a "thump" occurring during large gain change and generally should be avoided.

It is desirable also that the detector used to sense signal level in an automatic gain control system should respond to both positive and negative excursions of the signal. This provides a more accurate determination of level and produces less signal distortion.

In a hearing aid, such an AGC system may be placed in the signal path from microphone to receiver. The level detector is properly located in this signal path at a point before the user-operated volume control. In this location, the system is called "input AGC", since the AGC action depends on the input signal level, independent of the setting of the volume control.

If the hearing aid is also equipped with a wide-range tone control, or adjustable filter, it is also desirable that the AGC level detector be placed at a point in the signal path after the filter. In this way, the AGC acts only on the range of frequencies actually being utilized. It would not act on signals rendered inaudible by filtering. If on the other hand, for example, if the AGC detector sensed signal levels before a four pole highpass filter, the AGC system would respond to otherwise inaudible low frequency components of the input signal. As a result the system would produce changes in gain that would unnecessarily and undesirably affect simultaneously occurring high frequency components of the input signal.

In many applications of such an AGC system, it must be as compact and efficient as possible. It must be of a form suitable for implementation on a monolithic integrated circuit and should require few components external to the integrated circuit clip and few interconnections. It should operate on low supply voltage and require little supply current.

Compansion System

In many electronic systems, it is necessary to transmit signals possessing a high dynamic range through a circuit or circuit element providing limited dynamic range. The dynamic range is the range of signal levels from the lowest useful signal level, usually determined by a noise level, to the highest useful signal level, determined either by the characteristics of the signal itself or by the limiting level or distortion characteristics of the circuit or element.

For example, in a hearing aid, an active filter with adjustable corner frequency normally requires the use of active circuit elements that have a limited dynamic range. With the input AGC system previously described, the active filter is located at a point in the signal path before the user-operated volume control; therefore the input signal level to the active filter cannot be adjusted by the user. If the input signal passes through the filter, the resulting dynamic range will be severely degraded.

This problem is similar to the problem of conveying signals through a transmission medium of limited dynamic range, for example, as in magnetic tape recording and playback. In such cases, some systems, such as the Dolby system, have been developed which compress the signal with some type of automatic gain control system before recording and expand the signal with another AGC system after playback. However, in such systems, the two AGC systems act independently of each other, with the result that attack and release transients are not cancelled out. See U.S. Pat. No. 4,377,792.

What is needed is a compression-expansion ("compansion") system that compresses the signal being applied to the circuit of limited dynamic range and expands the signal leaving that circuit in a substantially exact, complementary manner, without exhibiting attack and release transients at the output of the expander. This compansion system should be compact in size and efficient.

An electronic system may already include an amplifier whose gain is varied by a control signal, such as a hearing aid with an input AGC system. In this case, it is advantageous to consolidate functions. Instead of having two variable gain amplifiers, each controlled by its own control signal, it is better to use a single variable gain amplifier controlled by a composite control signal. This requires a compact, efficient circuit for combining control signals in the proper manner.

Output Limiting

In many electronic systems, such as hearing aids, the output signal level must increase indefinitely, but must be limited in some manner. Two techniques have been used for this purpose: peak clipping and output AGC limiting. In either case, it is often useful to have an adjustable limiting level.

In many circumstances, a peak clipper should limit the maximum output signal level to a limiting level selected by adjustment of a power level control. At the same time, the peak clipper should substantially maintain a constant gain as the power level control is adjusted for signal levels below the limiting level.

The clipper should clip both positive and negative excursions of the waveform symmetrically. It should also have an easily adjustable clipping level. It is also desirable that adjusting the clipping level should not change the frequency response for input signal levels below or well above the clipping level.

For many hearing aids with single-ended Class A output stages, the cliping level is adjusted by a variable resistor in series with the receiver. This arrangement does not produce symmetrical clipping. It also results in a hearing aid gain that changes with clipping level and a frequency response that changes with clipping level.

For many hearing aids with push-pull Class AB output stages, the clipping level is adjusted by a variable resistor in series with the center tap of a receiver. This

produces symmetrical clipping, but still results in a frequency response for high input signal levels that varies with the clipping level. Another problem with this arrangement is that the clipping level for a high variable resistor setting is very sensitive to the output stage bias current; this occurs since the voltage drop across the resistor produced by the bias current will subtract a substantial portion of the total output voltage range which varies with bias current.

In an output stage that drives an inductive load to saturation, such as the output stage of a hearing aid driving a magnetic receiver, the voltage at the output can swing below the lowest supply voltage. Often, for compact size, the output stage is included in a monolithic integrated circuit. In such an integrated circuit, the substrate is connected to the lowest supply voltage, and circuit elements on the integrated circuit are isolated from each other by reverse biased diode junctions between these elements and the substrate. If the voltage on an element swings below the substrate voltage, the normally reverse-biased isolation becomes forward biased, compromising the isolation between circuit elements. What is needed is a compact, efficient circuit to prevent the voltage from swinging substantially below the substrate voltage.

In many cases it is advantageous to limit the output signal level of an electronic system by using an output AGC system. If the AGC system holds the output level below clipping level, much less signal distortion occurs when limiting. In many cases, it is desirable that the output AGC system limit the output signal level to a limiting level selected by adjustment of a power level control while maintaining a constant gain as the power level control is adjusted for signal levels below the limiting level. Also it is advantageous to be able to select either peak clipping or output AGC action by operating a single switch. Furthermore, it is often desirable that the limiting levels for both peak clipping and output AGC be adjusted by a single power level control with the output AGC limiting level being just sufficiently below the peak clipping level to maintain low distortion.

When an output stage is driving a load whose impedance varies substantially with frequency, such as a hearing aid receiver, there may be some frequency regions in which output stage saturation is caused by a limited available output voltage and other frequencies regions in which output stage saturation is caused by a limited available output current. Also, when driving a load, such as a hearing aid receiver, high current levels may cause the receiver itself to produce distortion. For these reasons it is advantageous to have an output AGC system which detects both output stage signal voltage and output stage signal current and combines these detected signals in such a way as to cause the output AGC system to limit the output signal to just sufficiently below these saturation levels to maintain low distortion.

SUMMARY OF THE INVENTION

In a principal aspect the present invention is an improved hearing aid. In another aspect, the present invention is a hearing aid with a four pole adjustable corner state variable filter. According to one feature, the invention is simply a hearing aid having a microphone and receiver with a combination of filters. The filters are, respectively, a four pole adjustable corner lowpass filter, a four pole adjustable corner highpass filter, and an adjustable slope filter.

In another aspect, the present invention is an aid with an adjustable peak clipping circuit located before a fixed gain output stage. Yet still a further aspect is an aid with an adjustable output automatic gain control circuit whose level detector senses the signal level at the input of a fixed gain output stage. Still another aspect is an aid with an auxiliary automatic gain control detector circuit which detects both voltage and current at the output stage.

Another aspect of the present invention is an aid with an input automatic gain control circuit which provides independent adjustment of the compression threshold and compression ratio. A further aspect is an aid with a compansion system around the filter to increase its dynamic range.

In yet another aspect, the present invention is an aid having a control circuit to control the gain of an amplifier. The output of the control circuit is determined by a composite of signals from at least two of the following sources: the detector for the compansion system; the input automatic gain control detector; the output automatic gain control detector; a user-operated volume control; and a filter-adjusted gain control.

According to another principal aspect, the present invention is a resistorless variable corner frequency state variable filter. The filter includes a sum-difference amplifier, first and second feedback lines, and first and second integrators.

The sum-difference stage receives an input signal as well as signals from the first and second feedback lines. The output of the sum-difference stage is interconnected to the first integrator. The output of the first integrator is interconnected to the first feedback line, thu providing one of the inputs to the sum-difference stage. The output of the first integrator is also interconnected to the second integrator. The output of the second integrator is interconnected to the second feedback line, thus providing another input to the sum-difference stage.

In another aspect of the present invention, the state variable filter includes a control circuit. The control circuit receives an input control signal and responsively provides two control current outputs. A substantially constant ratio is maintained between the two current outputs as the input control signal varies. As a result, the characteristic frequency of the filter may be varied without substantially changing the quality factor of the filter.

In another aspect of the present invention, two 2-pole state variable filters are cascaded. A single control circuit receives an input control signal and responsively provides four control current outputs in appropriate ratios. Substantially constant ratios are maintained between the four current outputs as the input control signal varies. As a result, the characteristic frequency of the filter may be varied without substantially changing the filter shape, i.e. quality factor.

Yet another aspect of the present invention is a regulator for providing a range of reference voltages at an output terminal. This range of voltages is that which, when applied to the input terminals of matched transconductors, will produce a predetermined range of output currents from the transconductors. This regulator can be used, for example, as the control voltage input to the control circuit described above. The regulator includes five transconductors and two amplifiers.

The first and second transconductors are of a first polarity type and provide first and second output currents. The transconductance characteristic of the second transconductor has a first substantially fixed ratio to that of the first transconductor.

The third and fourth transconductors are of a second polarity type and provide third and fourth output currents. The transconductance characteristic of the fourth transconductor has a second substantially fixed ratio to that of the third transconductor.

The outputs of the second and third transconductor are connected together and provide the input to the first amplifier. The output of this amplifier is connected to the inputs of the third and fourth transconductors, acting as a feedback signal to force the third output current to be substantially equal to the second output current.

The outputs of the first and fourth transconductor are connected together and provide the input to the second amplifier. The output of this amplifier is connected to the input of the first transconductor, acting as a feedback signal to force the first output current to be substantially equal to the fourth output current.

The fifth transconductor is of the first polarity type. Its transconductance characteristic has a substantially fixed ratio to that of the first transconductor. The input of the fifth transconductor is connected to the output of the second amplifier. The output of the fifth transconductor is connected through the resistance of a potentiometer to the output of the second amplifier. The reference voltage output is taken from the wiper of the potentiometer.

Another aspect of the present invention is a variable slope filter for receiving an input signal and providing an output signal related to the input signal. The filter includes an input terminal, a differential transconductance amplifier, a capacitor, a unity gain differential amplifier, a potentiometer, and a ground line.

The differential transconductance amplifier receives the input signal and a feedback signal from its output and provides an output current. The capacitor is interconnected between the transconductance amplifier output line and the ground line. The unity gain differential amplifier is interconnected to the input terminal and the output of the transconductance amplifier. The unity gain differential amplifier senses difference between the input signal and the transconductance amplifier signal and responsively provides an output signal at its output line.

The potentiometer is interconnected between the transconductance amplifier output line and the unity gain amplifier output line. The output signal from the variable slope filter is taken from the wiper of the potentiometer, which can be adjusted to make the filter either a low pass, high pass or flat response filter.

Another principal aspect of the present invention is an automatic gain control ("AGC") system for receiving an input signal and providing a compressed output signal and providing an adjustable compression threshold and an adjustable compression ratio. The AGC system includes a primary controlled amplifier, a secondary controlled amplifier, a threshold detector, a control circuit, a compression threshold control, and a compression ratio control.

The input signal is applied to the inputs of the primary controlled amplifier and the secondary controlled amplifier. The output of the secondary controlled amplifier is applied to the input of the threshold detector, which detects when the output signal from the secondary controlled amplifier exceeds a predetermined level. The output of the threshold detector is connected to a control circuit.

The control circuit combines the output of the threshold detector with a control signal from the compression threshold control and develops a secondary control signal which is applied to the control input of the secondary controlled amplifier. This forms a feedback system to reduce the gain of the secondary controlled amplifier when the signal level at the output of the secondary controlled amplifier exceeds the threshold level of the threshold detector. This, in turn, occurs at an input level to the secondary controlled amplifier that is established by the control signal from the compression threshold control.

The output of the threshold detector is also applied to the compression ratio control, which provides an adjustable portion of this output as a primary control signal to the control input of the primary controlled amplifier. The output of this amplifier is the compressed output signal from the AGC system.

According to another aspect, the present invention is a differential voltage threshold detector for sensing when the difference between the voltages applied to first and second input terminals exceeds a predetermined threshold. This detector, may be used, for example, in the AGC system just described. The detector includes a differential transconductance stage, first and second "top" current mirrors, first and second "bottom" current mirrors, and a detector.

The differential transconductance stage senses the difference in the voltages at the first and second terminals and issues first and second output currents. The first and second top current mirrors sense these outputs. In response, each top current mirror issues two mirrored signals. Each bottom mirror sense one of the top current mirror signals and responsively provides a bottom current mirror signal.

The detector is interconnected to both of the top and bottom current mirrors. The detector senses when the second current mirror signal from the first top mirror substantially exceeds the signal from the second bottom mirror or when the second signal from the second top mirror substantially exceeds the signal from the first bottom mirror. Such a detection occurs when the voltage applied to the two input terminals varies by more than a predetermined amount. Accordingly, the detector issues an output signal.

In another aspect, the present invention is a bias current compensator. See U.S. Pat. No. 4,425,551. This bias current compensator may be used, for example, with the controlled amplifiers used in the AGC system previously described. The bias current compensator prevents bias current changes, caused by a varying control signal, from appearing in the output of the controlled amplifier. The bias current compensator includes a current source, first, second, and third transistors, and a feedback amplifier.

The current source supplies a known multiple of a predetermined collector current in a reference transistor. The emitter of the first transistor is interconnected to the current source and receives the current. The output of the second transistor provides current to the base of the first transistor. The third transistor is interconnected to the second transistor so that the current in the second transistor bears a predetermined relation to the current in the third transistor.

The input to the feedback amplifier is connected to the emitter of the first transistor. The output of the feedback amplifier is connected to the inputs of the second and third transistors. By means of this feedback, the base current of the first transistor is controlled so that the emitter current of the first transistor substantially equals that of the input current source.

The output of the third transistor is interconnected to the base of the reference transistor. Thus, by controlling the reference current source, the current supplied by the third transistor to the base of the reference transistor is accurately controlled.

Another aspect of the present invention is a compansion system for increasing the dynamic range of a circuit element that has a limited dynamic range. This system includes a first controlled amplifier, second controlled amplifier, threshold detector, and inverse amplifier.

The first amplifier includes an input signal lead and a control lead. The first controlled amplifier receives the input signal and amplifies the signal according to the signal applied to the control lead. The threshold detector is interconnected to the output of this first amplifier and the input of the "circuit element." It detects when the output of the amplifier exceeds a predetermined level and thus would exceed te dynamic range of the circuit element. When this occurs, the threshold detector provides a control signal to the control lead of the first amplifier to thereby reduce the gain of the first amplifier thereby compressing the range of signal levels at its output.

The second controlled amplifier is interconnected to the output side of the circuit element. The second amplifier includes an input lead and a control lead as well. The second amplifier changes its gain in accordance with the control signal provided at its control lead.

The inverse amplifier is connected to the output lead of the threshold detector and receives the control signal that is received by the gain control lead of the first amplifier. The inverse amplifier, however, then inverts the signal and applies it to the control lead of the second controlled amplifier so that the increase in gain of the second controlled amplifier substantially equals the decrease in gain of the first controlled amplifier. The second controlled amplifier thus expands the range of signal levels at its output to substantially compensate for the compression of the range by the first controlled amplifier.

Another aspect of the present invention is a controlled current source for providing an output current substantially exponentially related to a difference between voltages on first and second input terminals and substantially linearly related to an input current applied to a third input terminal. The controlled current source includes first, second, and third transistors.

The controlled current source may be used, for example, to combine control signals from the AGC system and the compansion system described above. In this way, one controlled amplifier may be used instead of two. The first transistor is interconnected to the third input terminal to receive the input current and also is interconnected to the first input terminal to receive the voltage applied to it. The second transistor is interconnected to the first as a feedback stage to regulate the emitter voltage of the first and third transistors.

The third transistor is interconnected to the first transistor as well. The third transistor senses the voltage of the second input terminal and responsively provides an output current.

Another principal aspect of the present invention is a clipper circuit for limiting the predetermined maximum output of an amplifier. It includes first and second amplifiers. The first amplifier has a signal input interconnected to the input terminal and a feedback input interconnected to the output of the second amplifier. It responsively provides a first amplifier output signal.

The second amplifier is interconnected to the first amplifier and responsively provides an output signal. The second amplifier includes a control input and a variable current source. The maximum excursion of the second amplifier is limited by the current supplied to the control input.

The input to the second amplifier may conveniently be connected to a threshold detector to be used for an AGC system whose threshold is directly related to the adjustable clipping level.

In yet another aspect, the present invention is a voltage clamp to prevent a voltage at a node, and particularly a node in an integrated circuit, from becoming substantially negative with respect to a reference node, for example an integrated circuit substrate, and thus causing undesirable circuit operation. The clamp includes a reference voltage source, a voltage sensor, and a voltage supply.

The voltage sensor is interconnected to the node for providing variable conductivity between a voltage supply input and a sense input. The reference voltage source supplies a substantially constant reference voltage to a reference node. The voltage supply supplies the required current through the variable conductivity to the sense node.

GENERAL OBJECTS

A general object of the present invention is an improved hearing aid. Another object is a hearing aid with a wider range of control over its frequency responses. Still another object is a hearing aid with a wider range of control over its output level versus input level characteristics.

A further object of the present invention is a hearing aid with wider dynamic range, lower distortion and more consistent operation that will operate effectively on low supply voltage and is more compact, reliable, economical to use, and less expensive to manufacture.

SPECIFIC OBJECTS

Filters

An additional object of the present invention is a filter whose corner frequency may be varied more easily without changing the shape ("Q") of the frequency response curve of the filter. An additional object is an improved filter whose corner frequency may be so varied by adjusting a single control or "potentiometer".

A still further object is a filter whose corner frequency may be varied more easily by a control signal. Still a further object is a filter that uses a smaller number of substantially equal value capacitors. Another object is an improved filter using capacitors in which one end of each capacitor is interconnected to a common alternating current ("ac") ground. Another object is a filter that requires no resistors.

Still further object is a filter that allows a low voltage operation from a single cell power source and that uses a lower current drain. Yet a still further object of the present invention is a filter that may be more easily implemented on a semi-custom integrated circuit. Yet a still further object is a filter whose response curve shape

is greatly determined by an integer number of substantially identical transistors inter connected in parallel. Another object is a filter that more conveniently provides low pass, band pass and high pass outputs simultaneously.

Yet still an additional object is an improved regulator that:

- More accurately controls current sources, such as, for example, those used to control filter corner frequency;
- Provides an output that can be more easily adjusted over a predetermined range;
- In which a reference current is better established using a single resistor;
- In which the range is more precisely defined by the use of integer numbers of substantially identical transistors in parallel;
- Has lower sensitivity to transistor beta;
- Operates with lower supply voltage;
- Requires less supply current; and
- Is more compact.

An additional object is an improved variable slope filter that:

- Requires just one capacitor having one terminal interconnected to a common "ac" ground and is adjustable from single pole low pass to single pole high pass with an intermediate flat response;
- Requires no resistors other than a potentiometer and provides more accurate control of response;
- Operates with lower voltage, lower current, is more compact;
- Is less expensive to manufacture.

Input AGC

Still an additional object is an input automatic gain control circuit that:

- More accurately controls the compression threshold;
- More accurately controls the compression ratios;
- Allows the compression threshold to be more independently adjustable by a single control;
- Allows the compression ratio to be more independently adjustable by a single control;
- Operates with lower voltage, lower current, is more compact; and
- Is less expensive.

Still an additional object of the present invention is an improved threshold detector that:

- More accurately determines low voltage thresholds; and
- More effectively utilizes a differential input and is inherently a full wave detector.

An additional object is a bias current compensation circuit that operates on lower supply voltage and provides more accurate and reliable operation.

Compansion System

Another object of the present invention is an improved compansion system that:

- More effectively increases dynamic range of other circuit elements;
- More effective uses a single threshold detector (or level detector) and detector filter;
- Provides superior transient characteristics during attack and release;
- Utilizes a low supply voltage and low supply current; and
- Is more compact.

A further object is an improved voltage controlled, exponential current source that:

- Allows gain controlling signals to be combined into a single composite control signal;
- Reduces the number of variable gain amplifiers required; and
- Provides a flexible controlled current source with both linear control input and exponential control input.

Output Limiting

Still further objects of the present invention are as follows:

- An improved adjustable peak clipper with more symmetrical clipping of positive and negative peaks;
- A clipper that allows voltage gain to remain more substantially constant as the clipping level is adjusted;
- A clipper whose clipping level is substantially independent of supply voltage;
- A clipper providing a clipping level not based on junction voltage;
- A clipper that provides an output signal with which a threshold detector may provide an AGC control signal which is related to clipping level;
- A circuit that more easily allows for clipping and/or AGC level established before a fixed gain output stage to provide a constant frequency response as clipping level is adjusted; and
- A circuit that more easily allows the clipping and AGC systems to be used on different kinds of output stages.

Another object is an output stage with AGC detectors that more accurately detect both output voltage and output current so that maximum output may be limited by AGC to below the voltage and current levels which would produce distortion, either in the output stage or the load.

An additional object is an improved voltage clamp that prevents voltage swings (with an inductive load) from going substantially below the substrate voltage of an integrated circuit which would disturb operation.

These and other objects of the present invention will be more fully understood by reference to the following detailed description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWING

Preferred embodiments of the present invention are described herein with reference to the drawing wherein:

General Circuit

FIG. **1** is a block diagram of the preferred embodiment of the hearing aid of the present invention;

FIG. **2** is a more detailed block diagram of the preferred embodiment of the hearing aid shown in FIG. **1**;

Sub-Systems

FIG. **3** is a block diagram of an adjustable state variable filter for the preferred embodiment shown in FIG. **1**;

FIG. **4** is a block diagram of an adjustable state variable filter, showing an alternative embodiment of the filter shown in FIG. **3**;

FIG. **5** is a block diagram of an adjustable state variable filter, showing another alternative embodiment of the filter shown in FIG. **3**;

FIG. **6** is a symbolic representation of the unity gain sum/difference amplifier used in the preferred embodiment of the filter shown in FIG. **3**;

FIG. **7** is a schematic diagram of the unity gain sum/-difference amplifier used in the preferred embodiment shown in FIG. **3**;

FIG. 8 is a more detailed schematic diagram of the unity gain sum/difference amplifier used in the preferred embodiment shown in FIG. 3;

FIG. 9 is a symbolic representation of the integrator used in the preferred embodiment shown in FIG. 3;

FIG. 10 is a schematic diagram of the integrator used in the preferred embodiment shown in FIG. 3;

FIG. 11 is a more detailed schematic diagram of the integrator used in the preferred embodiment shown in FIG. 3;

FIG. 12 is a schematic diagram of the control circuit used in the preferred embodiment shown in FIG. 3;

FIG. 12*a* is a schematic diagram of a control circuit showing an alternative embodiment of the control circuit shown in FIG. 12;

FIG. 13 is a schematic diagram of the filter shown in FIG. 3;

FIG. 14 is a more detailed schematic diagram of the filter shown in FIG. 3;

FIG. 15 is a block diagram showing how the two pole filter shown in the preferred embodiment of FIG. 3 may be used to make a four pole high pass filter;

FIG. 16 is a block diagram showing how the two pole filter shown in FIG. 3 may be used to make a four pole low pass filter;

FIG. 17 is a schematic diagram of a control circuit used in the preferred embodiment shown in FIG. 15;

FIG. 18 is a schematic diagram of a control circuit showing an alternative embodiment of the circuit shown in FIG. 17;

FIG. 19 is a schematic diagram of the differential threshold detector for the preferred embodiment shown in FIG. 1;

FIG. 20 is a more detailed schematic diagram of the differential threshold detector shown in FIG. 19.

FIG. 21 is a schematic diagram of the system for increasing dynamic range for the preferred embodiment shown in FIG. 1;

FIG. 22 is a schematic diagram of an operational transconductance amplifier, as used with the preferred embodiment shown in FIG. 1;

FIG. 23 is a schematic diagram of the controlled current source for the preferred embodiment shown FIG. 1;

FIG. 24 is a schematic diagram of the regulator for the preferred embodiment shown in FIG. 1;

FIG. 24*a* is a schematic diagram of a first amplifier used in the regulator shown in FIG. 24;

FIG. 24*b* is a schematic diagram of a second amplifier used in the regulator shown in FIG. 24;

FIG. 25 is a schematic diagram of the variable slope filter for the preferred embodiment shown in FIG. 1;

FIG. 26 is a schematic diagram of the clipper circuit for the preferred embodiment shown in FIG. 1;

FIG. 27 is a schematic diagram of the voltage clamp for the preferred embodiment shown in FIG. 1;

FIG. 28 is a schematic diagram of the bias current compensation circuit for the preferred embodiment shown in FIG. 1;

FIG. 29 is a block diagram of the input automatic gain control system for the preferred embodiment shown in FIG. 1; and

FIG. 30 is a graph demonstrating the effect of the automatic gain control system of FIG. 29.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

General System Description

Referring to FIGS. 1–30, the preferred embodiment of the present invention is shown as an improved hearing aid circuit, generally designated 20. Significantly, many of the circuits described herein may be used in a variety of different applications. However, the most preferred embodiment of the present invention relates to hearing aids. Thus, the invention has been described in the context of hearing aids.

As shown more clearly in FIG. 1, a hearing aid (not shown) includes a signal source or microphone 22, a "compander" 24, a filter or "tone control network" 26 and related external controls 28, an input Automatic Gain Control ("AGC") system 27 and related external controls 35, a main current controlled amplifier ("CCA") 32 and related external controls 34, an output signal processor 36 and related external controls 38, and a receiver or output transducer 40.

In several figures, dotted lines are drawn about selected circuit components. Such groupings of circuit components has been made somewhat arbitrarily and only as an aid to the reader in understanding the present invention.

As shown in FIGS. 1 and 2, the microphone 22 receives sound signals in the air and responsively transmits an electrical signal along a signal path 42, represented as heavy lines in FIGS. 1 and 2. Certain circuit components affect the electric signal indirectly, by affecting the operation of circuit components, rather than the actual signal itself. The signals from such components are sent via control paths, which are represented by the lighter lines 44 shown in FIGS. 1 and 2.

Electrical signals generated by the microphone 22 have relatively small amplitude and are received by the compander 24. The compander 24 includes input current controlled amplifier 46, a "compand" detector 48, a "compand" filter 50, and an input current controlled amplifier control 52 to vary the gain of the current controlled amplifier 46.

The current controlled amplifier 46 simply increases the amplitude of the microphone signal in a predetermined manner for processing by the rest of the hearing aid circuit 20. The "compand" detector 48 senses when the output of the current controlled amplifier 46 exceeds a predetermined level, outside of the dynamic range of the filter 26.

When the "compand" detector 48 senses such a large signal from the current controlled amplifier 46, it sends a signal to "compand" filter 50. The "compand" filter 50 issues a smoothed compand detector signal, which is received by both the current controlled amplifier control 52 the main CCA control 68 and the secondary CCA control 706. The input current controlled amplifier control 52 then reduces a controlling current which it supplies to the input current controlled amplifier 46 to decrease the amount of amplification exerted by the amplifier 46.

The controlling current from the input current controlled amplifier control 52 is exponentially related to the amplitude of the signal received from the "compand" filter 50. The controlling current received by the main CCA 66 is inversely related to the controlling current to the input CCA 46. The gain of the main CCA 66 is thus inversely related to the gain of the input CCA 46. In this way, the gain through the system is constant, but the filters in the tone control network 26 operate over a narrower dynamic range of signal levels.

The output of the current controlled amplifier 46 is received by the tone control network 26. The tone

control network **26** includes a four pole lowpass filter **54**, which presents a signal to a four pole highpass filter **56**. The two filters **54, 56** are controlled, respectively, by the potentiometers, or controls **58, 60**. The settings of the potentiometers **58, 60** determine the frequency at which the low pass and high pass filter **54, 56** will start substantially influencing the signal received.

A signal from the lowpass and highpass filters **54, 56** is transfered to the variable slope filter **62**, which further shapes the frequency spectrum of the signal. The variable slope filter **62** presents two signals to a variable slope control **64**, which may be adjusted to further attenuate high frequency signals, low frequency signals, or to pass all frequencies equally.

The variable slope control **64** provides a signal to the input AGC circuit **27** and the main amplifier **32**. The main amplifier **32** includes the main current controlled amplifier **66** and the main current controlled amplifier control **68**. Two external adjustments, a user operated volume control **70** and a full on gain control **72**, are interconnected to the main current controlled amplifier control **68**. Control **68** also receives inputs from the compander **24**, the output signal processor **36**, and the input AGC system **27**, which are used to control the gain of the main current controlled amplifier **66**.

Thus, when the compander **24** is operating, it sends a signal to the main current controlled amplifier control **68** so that the input to the main amplifier **32** is expanded to the same degree that it was compressed by the input current controlled amplifier **46**.

The level of gain that the main current controlled amplifier **66** exhibits is determined, in part, by the inputs to the control **68**, including the setting of the user operated volume control **70**. The maximum gain obtainable with the user operated volume control **70** full on is established in part by the setting of the full on gain control **72**.

The input AGC system **27** includes a secondary CCA **700**, an AGC Detector **702**, AGC filter **704**, secondary CCA control **706**, and associated external controls **35** including the AGC threshold control **710** and AGC CR (compression ratio control) **712**. In addition the system uses portions of the main amplifier **32**, including the main CCA **66** and a portion of the main CCA control **68**.

The input AGC system uses a feedback system to establish the control signal, and this control signal is fed forward to the main CCA **66**. The secondary CCA **700** amplifies the signal from the variable slope control **64** and sends this amplified signal to the AGC detector **702**. The AGC detector **702** senses when the output of the secondary CCA **700** exceeds a predetermined level, called the AGC detector threshold level.

When the AGC detector **702** is triggered by an input reaching or exceeding the threshold level, it sends a signal to the AGC filter **704** which issues a smoothed AGC detector signal (called V_{c1}), which is received by the secondary CCA control **706**. The secondary CCA control **706** supplies a control current to the secondary CCA **700** to control its gain. This control current is controlled by both the smoothed detector signal (V_{c1}) and an external control, the AGC threshold control **710**. The detector signal (V_{c1}) causes the control current to be reduced, which reduces the gain of the secondary CCA **700** such that its output signal amplitude does not substantially exceed the AGC detector threshold level.

The signal level from the microphone required to trigger the AGC detector **702** is called the input AGC threshold. The AGC threshold control **710** also varies the gain of the secondary CCA **700** so as to vary the input AGC threshold.

The secondary CCA control **706** also receives an inverse controlling signal from the compand filter **50** to expand the previously compressed signal which is present at the variable slope control **64** output. In this way the compansion action will not influence the detector signal V_{c1} and the compander will not be "seen" by the input AGC system.

If this smoothed detector signal (V_{c1}) is applied to the main CCA control **68**, the result would be an AGC system with a very high non-variable compression ratio (CR) above the AGC threshold. To provide variable slope compression, the detector signal (V_{c1}) from the AGC filter **704** is passed through a variable control, the AGC CR control **712**. The AGC CR control **712** can provide an adjustable portion of the detector signal to the main CCA control **68**, which controls the gain of main CCA **66**. Thus, for input levels above the AGC threshold, the amount of gain reduction which the input AGC system exerts on main CCA **66** is variable by means of the AGC CR control **712**, thereby varying the slope of the input-output curve above the threshold.

The output of the main current controlled amplifier **66** is received by the output signal processor **36**. The output signal processor **36** includes a clipper **74**, output amplifier **76**, output current detector **78**, voltage output detector **80**, AGC detector **86**, internal automatic gain control switch **82**, and AGC filter **84**. An external AGC switch **88** and a power level control **90** are interconnected to the output signal processor **36**.

The clipper **74** prevents any signal received from the main current controlled amplifier **66** from exceeding a certain predetermined output level set by the power level control **90**. The output of the clipper **74** is sent to the output amplifier **76**, and a secondary output is sensed by the automatic gain control detector **86**.

The output amplifier **76** further increases the signal received from the clipper **74**, before it is sent to the receiver **40**. Current and voltage detectors **78, 80** sense the output current and voltage and provide output signals to the AGC switch **82** when either the output current or the output voltage exceeds a respective predetermined level.

The automatic gain control switch **82** may be switched on with the external AGC switch **88**. Signals from the current and/or voltage detectors **78, 80**, or from the automatic gain control detector **86** signify that the output of the circuit **20** is too large. Such signals are thus transmitted to the automatic gain control filter **84**, which smooths and combines these signals and feeds them back to the main current controlled amplifier control **68** to reduce the amount of gain which the main current controlled amplifier **66** is then providing.

A signal from the output amplifier **76** is applied to the receiver **40**, which converts the electrical signal to sound. This sound is then heard by the wearer of the hearing aid.

System Architecture

Much of the advantages of the present system arise from the architecture or placement of the various components. In particular, a compression circuit and an expansion circuit are placed on opposite sides of the voltage controlled filters to increase the dynamic range of the system. See FIG. **21**. Moreover, the adjustable

peak clipping circuit or clipper **74** is positioned before the fixed gain output stage or output amp **76**. As a result, the previously mentioned design problems of providing adjustable clipping at the output of the output stage, such as asymmetrical clipping and sensitivity to output stage bias current, are avoided.

In addition, the adjustable output automatic gain control circuit is located before the fixed gain output stage. As a result, the output automatic gain control may be connected to the clipper **74** to allow the power level control **90** to determine the output limiting level in both AGC and non-AGC modes. In addition, the auxiliary automatic gain control uses both output voltage and output current detection systems **80, 78** at the output stage.

By adding a fixed amplitude detection system at the output of the output stage, a greater undistorted maximum output level from the output stage during use of the output automatic gain control may be safely designed for. This is because the tolerances of the detection level occurring at the input of the output stage as well as the output stage gain do not require that the detection level be set lower to prevent possible clipping in the output stage when the output level control is set to maximum. Instead, the detection level may be set high enough to substantially guarantee full use of the output amplifier's amplitude capability and the fixed amplitude detection at the output of the output stage will override the detection at the input of the output stage when the output level control is set to maximum.

The output voltage detection simply triggers the output automatic gain control if the collector to emitter voltage of the output stage transistors nears saturation, thus preventing clipping and resultant distortion.

The output current detection monitors the current delivered to the receiver and also triggers the output automatic gain control if a predetermined current limit is exceeded. This has a major advantage in the preferred embodiment which is a high power hearing aid. The current state of the art in receiver design produces receivers with widely fluctuating impedance versus frequency which, at some frequencies, can drop very low compared to the average impedance value. When driven by an amplifier capable of driving the receiver to maximum levels where the receiver exhibits nominal impedance, the receiver may draw excessive current from the amplifier at frequencies where receiver impedance is much lower, either exceeding the receiver's own current limits for low distortion operation or possibly the amplifier's linear operation region, which could also increase distortion. Thus, having both current and voltage detection utilizes the maximum output capability of the amplifier-receiver system across the frequency range of the system.

In addition, the input automatic gain control circuit uses independent adjustment of the compression threshold and compression ratio and allows for precise adjustment of each of these factors without interaction between the adjustments.

In addition, level detection for the input automatic gain control circuit is located after the tone (or frequency shaping) control **26**, but still before the gain control. Applicants have found that such an arrangement provides a more desired signal, since the AGC system is operating on the signal eventually supplied to the receiver and "heard" by the wearer of the aid **20**. In other arrangements, the AGC system may operate on signals not yet shaped by the filter, or tone control.

Normally, it is desired that selected frequencies of sound signals not passed by the filter, and thus not intended to be amplified by the aid, should not affect the operation of the aid. Since the AGC system of the present invention does not operate on such signals, since they may be effectively attenuated by the filter, such extraneous noise will not significantly influence the operation of the AGC system.

Thus, for example, the filter may be adjusted such that low frequency signals, such as the low frequency sounds emitted by heavy machinery, will be substantially attenuated by the filter. If the AGC level detection occurs before the filter, these signals could cause the AGC system to respond and reduce the gain for higher frequency desired signals. However, the present AGC would not respond to these low frequency signals when they are outside of the filter pass band.

Moreover, the main current controlled amplifier uses a control signal which is a composite of signals. The composite of signals is derived from a plurality of inputs from different sections of the aid. The signal is comprised of the signal from the compander **24**, the input AGC system **27**, the output signal processor **36**, the user-operated volume control **70**, and the full-on gain control **72**. By using such a composite of signals, a single current controlled amplifier **66**, rather than a series of amplifiers, may be used. This reduces the noise generated and complexity of the circuit, as well as allowing the circuit to be made more cheaply.

The hearing aid circuit **20** is comprised of different, smaller circuits. Several of these smaller circuits for the overall hearing aid circuit **20** are individually discussed in detail in separate sections below:

Adjustable State Variable Filter

Referring to FIGS. **3–14**, one aspect of the present invention is an improved adjustable two pole state variable filter generally designated **410**. The filter, as shown in FIG. **3**, includes a unity gain sum-difference amplifier **411**, first and second variable integrators **413, 415**, each including a capacitor loaded operational transconductance amplifier ("OTA") **416, 418**, loaded, respectively, by capacitors **424, 426**, first and second feedback lines **420, 422**, an input terminal **428**, and ground line **429**, and highpass, bandpass, and lowpass output terminals **430, 432, 434**.

The input signal from the input terminal has a positive input to the sum-difference amplifier **411**. The first feedback line **420** has a second positive input and the second feedback line **422** has a negative input. The output of the sum-difference amplifier **411** in conjunction with the rest of the circuit **410** results in the highpass signal at the output of the sum-difference amplifier **411**.

The output of the amplifier **411** is interconnected to the highpass output terminal **430**. The output is also interconnected to the negative input of the first integrator **413**. The first integrator **413** receives the high-pass signal and responsively provides at its output a first integrated signal which corresponds to a bandpass signal and which is interconnected to the bandpass output terminal **432**. It also provides this signal to the first feedback line **420** to provide one of the positive inputs to the sum-difference amplifier.

The output of the first integrator **413** is also supplied as an input to the second integrator **415**. The second integrator **415** responsively provides an output which is provided to the output lowpass terminal **434** and the second feedback line **422**. The second feedback line **422**,

of course, provides a negative input to the sum-difference amplifier **411**.

The operation of an ideal OTA is given by the following formula:

$$g_m = h(I_x)$$

where g_m is the transconductance (or gain) of the OTA, h is a constant of a particular OTA, and I_x is the control current supplied to the OTA. Output current of the OTA is provided by the following equation:

$$i_{output} = g_m[(V+)-(v-)]$$

where I output is the output current and v+ and v− are, respectively, the positive and negative voltages applied to the differential inputs of the OTA. A simple OTA realization using bipolar transistors is shown in FIG. **22**. For this configuration, which includes a differential transistor pair with a current mirror load and a current source I_x supplying an emitter current for the differential pair, $g_m = I_x/2\ V_T$, where V_T is the volt equivalent of temperature $= kT/q_e$. See, e.g., R. Gray & R. Meyer, Analysis and Design of Analog Integrated Circuits (John Wiley & Sons 1977).

An equation is often provided for a filter to indicate how the output signal of the filter is related to any input signal applied to the filter. Such equations are known as "transfer functions." Generally, the steeper the slope of the attenuation versus frequency curve of the signal beyond the corner frequency, the more "poles" of the transfer function describing the filter. Poles define situations in which the denominator of the theoretical transfer function substantially reaches zero for a given input signal frequency.

Equations describing the outputs for the circuit shown in FIG. **3** are listed below:

Unity Gain

Sum/Difference Amplifier: $v_2 = v_1 + v_3 - v_4$

Variable Integrators: $v_3 = -(g_{m1}/jwC_1)\ v_2$

$v_4 = (g_{m2}/jwC_2)\ v_3$

where $j = \sqrt{-1}$ and $w = 2\pi$ times the signal frequency.

$$\text{High Pass: } \frac{v_2}{v_1} = \frac{-w^2}{w_o^2 - w^2 + (jw)(w_o)/Q}$$

$$\text{Band Pass: } v_3/v_1 = \frac{-(jW)(W_o)}{W_o^2 - W^2 + (jW)(W_o)/Q}$$

$$\text{Low Pass: } v_4/v_1 = \frac{W_o^2}{W_o^2 - W^2 + (jW)(W_o)/Q}$$

$$\text{where } W_o = \sqrt{\frac{g_{m1}\,g_{m2}}{C_1\,C_2}}\ ;\ Q = \sqrt{\frac{g_{m2}\,C_1}{g_{m1}\,C_2}}$$

W_o is known as the characteristic frequency; Q is known as the quality factor (or the inverse of the damping factor).

$g_{m1} = hI_{x1}$; and $g_{m2} = hI_{x2}$

where, again, h is a constant for a particular transconductance amplifier.

If we make $C_1 = C_2 \equiv C$ then

$$W_o = (h/c)\sqrt{I_{x1}\,I_{x2}} \text{ and } Q = \sqrt{I_{x2}/I_{x1}}$$

The present invention may be made substantially without the use of resistors using a minimal number of components. Moreover, the characteristic frequency and quality factor of the filter may be altered by changing the magnitudes of and ratio between I_{x1} and I_{x2}, which set the transconductances of the first and second OTAs **416**, **418**.

Of course, the present invention may be implemented with embodiments other than that shown in FIG. **3**. Thus, other, exemplary embodiments are shown in FIGS. **4** and **5**.

Also, the sum/difference amplifier **411**, integrator **413**, **415** and control circuit shown in FIG. **3** may be represented with a variety of embodiments. Three different but equivalent representations of the unity gain sum/difference amplifier are shown in FIGS. **6**, **7**, and **8**. FIG. **6** is a symbolic representation of the sum-difference function having two positive input terminals and a negative input terminal. The output voltage v_d is related to the inputs as follows, $v_d = v_a - v_b + v_c$. This representation is numbered **411** in FIG. **3**.

FIG. **7** is a realization of this function using operational transconductance amplifiers **412**, **414**, where the control currents I_{xa} and I_{xb} set the transconductance values g_{ma}, and g_{mb}. If $I_{xa} = I_{xb}$, $g_{ma} = g_{mb} \equiv g_m$.

If the loading on the output of amplifier **414** is negligible (i.e. output current i_l is very small)

$$i_{oa} = -i_{ob}$$

and

$$g_m(v_a - v_b) = -g_m(v_c - v_d)$$

which gives

$$v_d = v_a - v_b + v_c.$$

FIG. **8** is a transistor realization of FIG. **7** in which two OTA's as shown in FIG. **22** have been combined in a simplified form. In FIG. **8**, the difference between the collector currents of transistors **472**, **474**, $(i_a - i_b)$ and transistors **480**, **478** $(i_c - i_d)$ corresponds to the currents i_{oa}, and I_{ob} respectively of FIG. **7**. These differences could be performed by the standard PNP current mirror loading of a differential NPN pair as configured in FIG. **22**. However, in FIG. **7**, i_{oa}, and i_{ob} are summed. Therefore, $i_{oa} + i_{ob} = (i_a - i_b) + (i_c - i_d)$ which can be rearranged to give:

$$i_{oa} + i_{ob} = (i_a + i_c) - (i_b + i_d)$$

which shows that the collector currents of transistors **474** and **478** may be summed first (by paralleling) and combined with the output current of a single PNP current mirror whose input is the sum of the collector currents (by paralleling) of transistors **472** and **480**. Thus, only one PNP mirror (dual collector transistor **496**) is required.

Similarly, three different but equivalent representations of a variable integrator are shown in FIGS. **9**, **10**,

and **11**. For the symbolic representation of a differential, variable integrator shown in FIG. **9**, for example, the output is given by the following equations.

In the time domain:

$$v_c = KI_x \int (v_a - v_b)dt$$

where I_x is a control current and K is a proportionality constant.

In the frequency domain:

$$v_c = (KI_x/jw)(v_a - v_b)$$

The integrator shown in FIG. **10** is an OTA with a capacitor load. The output current for the OTA is given by the equation below:

$$i_o = g_m(v_a - v_b); \text{ where } g_m = hI_x$$

The voltage across a capacitor is equal to the integral, over time, of the current through the capacitor. Or, in the frequency domain: $v_c = i_o/jWC$. Thus, loading the OTA with a capacitor with no additional loading gives:

$$v_c = \frac{g_m}{jWC}(v_a - v_b) = \frac{h\,I_x}{jWC}(v_a - v_b)$$

For the representation of an integrator shown in FIG. **11**, the OTA has been realized with the transistor equivalent shown in FIG. **22**. The equation is shown below:

$$g_m = \frac{I_x}{2\,V_T}$$

With no external loading, all of the current i_o flows into the capacitor and:

$$v_c = \left(\frac{I_x}{2V_T}\right)(1/jWC)(v_a - v_b)$$

Finally, first and second embodiments **501, 503** of a control circuit are shown in FIGS. **12** and **12***a*. The embodiment of the control circuit **501** shown in FIG. **12** receives a frequency control current, designated I_w, and respectively provides related control currents I_{x1} and I_{x2}. The control circuit **501** includes a transistor **505** having an interconnected base and collector. The transistor **505** develops a base to emitter voltage, which is related to the frequency control current applied to the base and collector of the transistor **505**.

The control circuit **501** also includes first and second control transistors **507** and **509**. Each of the transistors **507, 509** receives the base to emitter voltage developed by transistor **505** and provides a collector current designated, respectively, I_{x1} and I_{x2}.

As shown in FIG. **12**, the transistors **507–509** are each single devices. In the preferred embodiment, the collector currents of the first and second control transistors **507** and **509** are, respectively, n_1 and n_2 times the collector current of the transistor **505**, which is substantially equal to the control current I_w. This may be accomplished using only substantially identical transistors as would be available on a semi-custom integrated circuit, by having n_1 devices connected in parallel in place of the first control transistor **507** and n_2 devices connected in parallel in place of the second control transistor **509**. Alternatively, the emitter area of the transistor **505** and first and second control transistors **507, 509** can bear a relationship to each other, respectively, of 1 to n_1 to n_2.

Consequently, if the transistors **505, 507, 509** each have high current amplification characteristics ("betas"), then $I_{x1} = n_1 I_w$ and $I_{x2} = n_2 I_w$. The currents I_{x1} and I_{x2} then control the operation of the filter such that the filter corner frequency is linearly related to the frequency control current, I_w and the quality factor remains constant as the frequency control current is varied.

The embodiment of the control circuit **503** shown in FIG. **12***a* receives a frequency control voltage, designated V_w, and respectively provides related control currents I_{x1} and I_{x2}. The control circuit **503** includes first and second transistors **511, 513**. Each transistor **511, 513** includes a base to receive the frequency control voltage. The transistors **511, 513** then respectively provide collector currents I_{x1} and I_{x2}.

Again the collector currents of the two transistors **511, 513** may be multiples of some reference current. Such multiples, designated in FIG. **12***a* as n_1 and n_2 may, of course, be achieved by using similar transistors in parallel or by controlling the emitter-base junction areas of the transistor **511, 513**.

The collector currents, I_{x1} and I_{x2}, as before, control the filter. These currents are substantially described by the following equations:

$$I_{x1} = n_1 I_s \exp(V_w/V_T)$$

$$I_{x2} = n_2 I_s \exp(V_w/V_T)$$

where V_T again is the transistor thermal voltage, as previously defined, and I_s is a constant which is IC process dependent and temperature dependent. Notably, however, transistors formed on a single integrated circuit typically match well. The ratio of I_{x2} to I_{x1} is thus n_2/n_1.

To control I_x adequately, V_w should be derived from a regulator on the same chip. See, for example, the regulator with variable reference outputs shown in FIG. **24**.

The currents I_{x1} and I_{x2} then control the operation of the filter such that the filter corner frequency is exponentially related to the frequency control voltage, V_w, and the quality factor remains constant as the frequency control voltage is varied.

For a two Pole Butterworth Filter, $Q = 1/\sqrt{2}$

For $C_1 = C_2 \equiv C$, $Q = \sqrt{I_{x2}/I_{x1}}$

When $I_{x1} = 2I_{x2}$ then, by definition, $Q = \frac{1}{2}$ and the filter gives the classic Butterworth response.

Under this condition:

$$W_o = (h/C)\,I_{x2}\sqrt{2}$$

As shown in more detail in FIGS. **13** and **14**, the present invention includes a two pole filter **410**. The filter **410**, the basic building block for higher order filters, is shown in more detailed form in FIG. **13**. In this figure, the representation of the unity gain sum-differ-

ence amplifier shown in FIG. 7 is substituted for the more general representation of the unity gain sum-difference amplifier **411** shown in FIG. **3**.

The filter **410** is shown in a yet more detailed form in FIG. **14**. In this figure, the representation of the unity gain sum-difference amplifier **411** shown in FIG. **8** and the representation of the capacitor loaded opertional transconductance amplifiers **413, 415** shown in FIG. **11** are substituted for their more general representations shown in FIG. **3**.

Notably, one side of each capacitor is interconnected to the ac ground line. One end of all of the capacitors share a common node. As a result, the number of pad connections is reduced.

The two-pole filter **410** may, of course, be interconnected in tandem, as shown in FIGS. **15** and **16**, to achieve, respectively, a four pole highpass or a four pole lowpass filter. Filter control circuits which may be used with such filters are shown, for example, in FIGS. **17** and **18**, which are the same as the two pole control circuits of FIGS. **12** and **12*a***, with the addition of transistors identified by xn_3 xn_4 to supply control currents I_{x3} and I_{x4} to the second two pole filter section. Thus, for the four pole lowpass filter of FIG. **16**, the lowpass terminal **434** is interconnected to an input line of another filter which is structurally similar to the filter shown in FIG. **3**. The lowpass output terminal of this second two pole filter then provides a four pole lowpass filter response.

Similarly, the highpass output terminal **436** of the filter **410** may be interconnected to the input terminal of the second filter. (The second filter of course, is structurally similar to the filter shown in FIG. **3**) The highpass output terminal of the second filter then provides four pole highpass response. Two filters such as that shown in FIG. **3** may, of course, also be similarly interconnected to provide a four pole bandpass response.

For 4-Pole Butterworth Filter made up of two Cascaded 2-Pole Filters:

$$w_1 = w_o\, Q_1 = .5411$$

$$W_2 = W_o\, Q_2 = 1.306$$

The order of cascading does not affect frequency response.

If we make $C_1=C_2=C_3=C_4\equiv C$, then the current values may be set such that

$$I_{x2}/I_{x1} = Q_1^2 = .2928$$

and

$$I_{x4}/I_{x3} = Q_2^2 = 1.706$$

and

$$w_1 = w_2 = (h/C)\sqrt{I_{x1}\, I_{x2}} = (h/C)\sqrt{I_{x3}\, I_{x4}}$$

$$I_{x1}\,(.5411) = I_{x3}\,(1.306)$$

$$I_{x1}/I_{x3} = 2.414$$

which does not permit exact integer ratios between the currents I_{x1}, I_{x2}, I_{x3}, and I_{x4}. These ratios could be obtained in a custom integrated circuit design, where the emitter-base junction areas of transistors X_{n1} through X_{n4} can be made in non-integer ratios.

To approximate a 4-Pole Butterworth Filter with integer ratios:

$$\text{make}\quad I_{x1} = 3I_{x2}\quad Q_1 = \sqrt{1/3} = .577$$

$$2I_{x3} = I_{x4}\quad Q_2 = \sqrt{2/1} = 1.414$$

$$I_{x2} = I_{x3}\quad w_1/w_2 = \frac{(h/C)\, I_{x2}\sqrt{3}}{(h/C)\, I_{x3}\sqrt{2}} = 1.225$$

In many cases, this is an acceptable approximation to a Butterworth response.

It may be obtained with integer multiples of selected currents, which can be achieved on standard integrated circuits by using integer numbers of transistors connected in parallel. For a closer approximation, let I_w be the control current supplied by a single control circuit transistor. Then

$$I_{x1} = (7)\,(I_w),\ I_{x2} = (2)\,(I_w),$$

$$Q_1 = \sqrt{2/7} = .5345$$

$$I_{x3} = (3)\,(I_w),\ I_{x4} = (5)\,(I_w),$$

$$Q_2 = \sqrt{5/3} = 1.291$$

$$w_1/w_2 = \frac{(h/C)\, I_w\sqrt{14}}{(h/C)\, I_w\sqrt{15}} = .9661$$

The output of the low and high pass filter **54, 56** is received by the variable slope filter **62**. The filters **54, 56** and **62** modify the frequency response of the circuit **20**, and thus are generally referred to as tone controls.

Variable Slope Filter **62**

The hearing aid circuit **20** further includes a low element count, continuously variable slope response shaper, generally described as a variable slope filter **62**. The response of the variable slope filter **62** to an input signal may be continuously varied from a highpass through a flat response to a lowpass filter. As shown in FIG. **25**, the filter **62** includes an input terminal **178**, ground line **180**, first, second, and third transconductor amplifiers, **182, 184, 186**, lowpass, variable slope, and highpass output terminals **188, 190, 192**, a potentiometer **194**, and a capacitor **196**. The potentiometer **194** is the variable slope control **64** shown in FIG. **2**.

The filter **62** receives an input signal at the input terminal **178**. The first transconductor amplifier **182** includes first or positive and second or negative inputs **198, 200** and an output **202**. The positive input of amplifier **182** is interconnected to the input terminal **178** and receives the input signal. In response, amplifier **182** provides a first transconductor signal at its output **202**.

The capacitor **196** is interconnected between the first transconductor amplifier output **182** and the ground line **180**. The second or negative input **200** to the first transconductor amplifier **182** is interconnected to its output **202**. High frequency input signals are effectively shunted through the capacitor **196** to ground. Thus, the amplifier **182** and capacitor **196** form a single pole lowpass filter.

The second transconductor amplifier **184** also includes first (or positive) and second (or negative) inputs

204, 206 and an output 208. The first input is also interconnected to the input terminal 178. The second input 206 is interconnected to the output 202 of the first transconductor amplifier 202. The output 208 of the second transconductor amplifier is connected to the highpass terminal 192.

The third transconductor amplifier 186 includes first (or positive) and second (or negative) inputs 210, 212 and an output 214 as well. The first input 210 is interconnected to a reference voltage. The output 214 and second input 212 are interconnected to the output 208 of the second transconductor amplifier 184 and highpass terminal 192.

The third amplifier 186 presents a load impedance of approximately $1/g_{m3}$ to the second amplifier 184, such that the voltage gain of amplifier 184 is $A_{v2}=g_{m2}/g_{m3}$. If g_{m2} and g_{m3} are set equal, $A_{v2}=1$. This method of active loading procedures better linearity for high signal amplitudes by presenting the amplifier with a load whose nonlinearity is essentially complimentary to the nonlinearity of the amplifier being loaded.

The potentiometer 194 includes a wiper 216. The end terminals of the potentiometer 194 are respectively interconnected to the highpass and lowpass terminals 188, 192, and the variable slope terminal 190 is interconnected to the wiper 216 of potentiometer 194. By moving the wiper 216 from one end of the potentiometer 194 to the other, the output of the filter 62 gradually changes from that of a lowpass to a highpass filter. When in the middle, the terminal 190 provides a reasonably flat response output. The ratio of the voltages of the lowpass terminal 188 and input terminal 178 is given by the formula given below:

$$\frac{v_{out}}{v_{in}} = \frac{1}{1 + \frac{(jW)C}{g_{m1}}}$$

again where $j=-1$ and $w=2$ times the frequency of the signal, C is the value of the capacitor 196, and gm_1 is the transconductance of the first transconductor amplifier 182.

The lowpass filter has a corner frequency, f_c, equal to the following:

$$f_c = \frac{g_{m1}}{2\pi C}$$

where g_{m1} is the gain of the first transconductor (or amplifier) 182 and C is the value of the capacitor 196. If the gain of the second and thrid transconductor amplifiers 184, 186 is approximately equal, the highpass terminal voltage approximately equals the input terminal voltage minus the lowpass terminal voltage.

The ratio of the highpass terminal voltage divided by the input voltage is given by the formula below:

$$\frac{v_{out}}{v_{in}} = \frac{\frac{(jW)C}{g_{m1}}}{1 + \frac{(jw)C}{gm_1}}$$

The corner of this filter is then also at the frequency

$$f_c = \frac{g_{m2}}{2\pi C}$$

The potentiometer 194 has a relatively large value compared to the output impedances seen at the lowpass and highpass output terminals, 188, 192, in order to reduce loading of the resistor on the circuit. Such loading, of course, causes deviations from idealized highpass and lowpass filter responses. The output at the wiper 216 is a variable weighted sum of the highpass and lowpass terminal voltages.

In the preferred embodiment, the filter 176 uses only two discrete components: the capacitor 196 and the potentiometer 194. Thus, the present embodiment of applicant's invention reduces the elements required and size of the circuit.

In addition, the filter 62 provides for both highpass and lowpass outputs simultaneously. Moreover, varying the potentiometer 194 gives close to an apparent constant volume because there is some attenuation at all frequencies at the midpoint "flat" setting. Rotating the control away from the midpoint simultaneously reduces the output at one end of the frequency spectrum while raising the output at the opposite end of the frequency spectrum.

Differential Voltage Threshold Detector (e.g., "Compand" detector 48; AGC detector 702; Detector 86

The "compand" detector 48 must determine that the voltage emitted by the input current controlled amplifier 48 has increased sufficiently such that the "compand" circuitry should be activated. The "compand" detector 48 must accurately sense very small voltages, in the range of tens of millivolts, for proper operation. A sensitive voltage threshold detection circuit is thus required.

Prior art voltage threshold detection schemes frequently used a system in which a circuit compared a measured voltage to a standard reference voltage. A diode voltage drop of, for example, 0.6 or 0.7 volt, was often used as the reference voltage. In order to achieve sensitivity in the order of tens of millivolts, however, such prior art systems often required preamplification of the measured signal prior to sensing. This preamplification adds to the complexity and size of the system.

Moreover, differential full wave rectification of the signal to be sensed prior to threshold detection adds significantly to the complexity of the system. Thus, as shown in FIG. 19, the present invention 20 uses a differential voltage threshold detector 92 for sensing the difference between first and second terminals 94, 96, and providing an output signal at an output terminal 97 when the voltage differential exceeds a predetermined level.

As shown in FIGS. 19 and 20, the detector 92 includes a differential transconductance stage 90, two first and second "top" current mirrors 102, 104, first and second "bottom" current mirrors 106, 108, a detector 110, and a reference current source 115. The differential transconductance stage, having differential outputs, can be in the form of a differential pair of NPN transistors 111, 113, each having a base 112, 114, collector 116, 118, and an emitter 120, 122. The emitters 120, 122 are connected to the single reference current source 115 (which can be a transistor 117, as shown in FIG. 20). The bases 112, 114 are inter connected to the two input terminals

94, 96 between which the voltage differential should be sensed.

The tansistor 111 draws a first current (designated I_a) through its collector 116 and emitter 120. The transistor 113 draws a second current (designated I_b) through its collector 118 and emitter 122.

The two transistors 111, 113 are interconnected as a differential pair. Thus, the voltage difference between the input terminals 94, 96, and thus the two bases 112, 114 of the transistors 111, 113, determines the ratio of the currents I_a and I_b.

The first top mirror 102 is interconnected to the first transistor collector 116. The first primary mirror 102 senses the current I_a and responsively issues two other currents, which are multiples of current I_a. In FIG. 19, these currents are designated, respectively, as XI_a and YI_a.

The second top current mirror 104 is interconnected to the second transistor collector 118 in a similar manner. The second primary mirror 104 senses the current I_b and responsively issues currents which are multiples of the current I_b. Such currents are respectively designated as XI_b and YI_b.

The threshold detector 92 also includes first and second bottom current mirrors 106, 108. The first bottom current mirror 106 is interconnected to the top current mirrors 102, 104, as shown in FIG. 19, so as to receive the current YI_b. Similarly, the second bottom current mirror 108 is interconnected to the first and second top current mirrors 102, 104, as shown in FIG. 19, so as to receive the current YI_a.

In response to receiving the current YI_b, the first bottom current mirror 106 draws a multiple of the current YI_b designated as ZYI_b in FIG. 2. The leads carrying the currents XI_a and ZYI_b are joined at a first node 124.

Similarly, the lead carrying current YI_a is received by the second bottom current mirror 108, whereby the second bottom current mirror 108 draws a multiple of the current YI_a designated as ZYI_a in FIG. 2. The leads carrying the currents XI_b and ZYI_a are joined at a second node 126. The first and second nodes 124, 126 are interconnected to the detector 110. The detector 110 functions similarly to a logical NOR gate, although, of course, the type of output or output impedance may be different than that of a logical NOR gate.

Consequently, when the current XI_a is greater than or equal to the current ZYI_b, the voltage swings high at the node 124 and at the input of the detector 110. Similarly, the voltage swings high at the node 126 and at the other input to the detector 110 when XI_b is greater than or equal to the current ZYI_a.

Thus, when the difference between the voltages applied to the bases 112, 114 of the differential transistors 111, 113 exceeds a significant amount, the voltage swings high at one of the nodes 124, 126 and the threshold detector 92 is thereby enabled to sink a current at its output terminal 97. Such a signal signifies that the differential in voltage between the two input terminals exceeds a predetermined level.

A more detailed schematic, showing the transistor by transistor makeup of the detector 92 is shown in FIG. 20. In FIG. 20, the current mirrors 102, 104, 106, 108 are shown configured with transistors, and the current mirrors ratios x, y and z are set at 1, 2 and 1 respectively. The top mirrors 102, 104 are constructed with dual collector PNP devices (commonly available on semicustom IC's) whose collectors draw substantially equal currents, providing the function of 2 PNP devices with paralleled bases and emitters in the space required for one PNP device. For the above mirror ratios, detection occurs when $I_a \geq 2I_b$ or when $I_b \geq 2I_a$.

The ratio of the currents I_a and I_b in the threshold detector 92 may be approximated by the following formula:

$$\frac{I_a}{I_b} = \exp\left(\frac{\Delta V_{be}}{V_T}\right)$$

or

$$V_{be} = (V_T)\ln\left(\frac{I_a}{I_b}\right)$$

where V_{be} is the difference in voltage between the bases 112, 114 of the transistors 111, 113. For detection, $\Delta V_{be} \geqq V_T \ln(2)$ or $\Delta V_{be} \leqq V_T \ln(\frac{1}{2})$. Therefore, at room temperature, detection occurs when differences in the base to emitter voltages exceeds approximately ± 18 millivolts.

Thus, the detector 110 in the threshold detector 92 provides an output signal when the difference in voltages applied to the two terminals 94, 96 exceeds approximately ± 18 millivolts.

The present threshold detector 92 thus functions by comparing the ratioed collector currents of a differential pair. This arrangement includes an inherent differential/full wave operation, without the need for additional circuitry. Moreover, a voltage supply substantially as low as one volt may be used to power the present detector 92.

Compansion System (including, e.g. Compander 24 and a portion of the Main Amplifier 32)

See FIGS. 21 and 22. The compander 51 includes both a compression circuit 128 to limit the input signal amplitude to the filter 26, and an expansion circuit after the filter. The expansion circuit restores a linear input-output amplitude relationship and prevents overloading and subsequent distortion in the filter 26, thereby increasing the dynamic range of the filter.

As shown in FIG. 21, the compression circuit 128 includes an operation transconductance amplifier ("OTA") 132, threshold detector 134, load resistor 136, feedback bypass capacitor 138, detector filter capacitor 140, input lead 141, gain control terminal 152, and ground line 142. A more detailed schematic showing the transistor by transistor makeup of a typical OTA as used in the present invention, is shown in FIG. 22.

The "expansion" circuit includes a second OTA amplifier 144, load resistor 146, inverting amplifier 148, feedback bypass capacitor 150, and gain control terminal 154. In the preferred embodiment used in the hearing aid circuit, the first and second amplifiers 132, 144 are included in, respectively, the input current controlled amplifier 46 and main amplifier 32. The voltage threshold detector is comprised of the differential voltage detector 92 described above.

To clarify the description of the present invention, the input current controlled amplifier 46 and main amplifier 32 correspond to the first and second amplifiers 132, 144 in FIG. 21. Similarly, the capacitors 138 and 150 are actually a part of, respectively, input CCA 46 and main CCA 66 shown in FIG. 2. Also, the compand filter 50 is comprised of the detector filter capacitor 140.

In addition, the two load resistances **136, 146** are shown figuratively in FIG. **21** as discreet load resistances, whereas the amplifiers **46** and **32** as shown in FIG. **2** include these resistances. Moreover, the transistors **145** and **147** correspond to voltage controlled exponential current sources. Thus, the transistor **145** performs the functions of the input CCA control **52** and the transistor **147**, together with the inverting amplifier **148**, performs a portion of the function of the main CCA control **68**. Exponential current sources are further described in a following section. See, e.g., FIG. **23**.

An input signal is applied to the input lead **141**. The signal is then amplified by the first amplifier **132** and transmitted to the voltage controlled filter **131**. The threshold detector **143** senses if the signal provided by the first amplifier **132** is so large that it exceeds the proper dynamic range of the voltage controlled filter **131**. If so, the threshold detector **134** issues a gain control signal to both the gain control terminal **152** of the first amplifier **132** and the expansion circuit **130**.

The signal received via the gain control terminal **152** reduces gain of the first amplifier **132**. Thus, for example, upon sensing that the output of the first amplifier **132** exceeds a predetermined amplitude, such as 18 millivolts, the threshold detector **134** emits a signal to the base **149** of transistor **145**. The transistor **145**, in turn, supplies I_{x1} (which is exponentially related to the control voltage applied to base **149**) to the gain lead **152** of the first amplifier **132**. Consequently, the output of the first amplifier **132** is reduced to a level not substantially exceeding the predetermined amplitude.

In the preferred embodiment, the first amplifier **132** is a variable transconductor amplifier (see FIG. **22**) which provides a gain proportional to a gain control current (I_{x1}). The gain of the first amplifier is referred to as g_{m1}. When the detector **134** is not triggered, g_{m1} is determined by a gain reference voltage (V_{ref}) **143** applied to base **149** via resistor **141**, such that V_c substantially equals V_{ref}.

The output of the first amplifier **132** is received and modified by the tone controller filter **26** and then transmitted to the expansion circuit **130**. In the preferred embodiment, the second amplifier **144**, like the first amplifier **132**, is a transconductor amplifier with a gain control lead **154** whose gain (g_{m2}) is controlled by I_{x2} which is supplied by transistor **147**.

The inverting amplifier **148** receives the same signal applied to the base **149** and inverts the difference between this voltage (V_c) and V_{ref} and responsively applies a signal V_{EX} to the base lead **151** of the transistor **147** such that $V_{EX}=V_{ref}+(V_{ref}-V_c)$. The second amplifier **144** then receives the inverse of the gain control signal provided to the first amplifier **132**. Consequently, the gain control "function" applied to the signal by the second amplifier **144** ("g_{m2}") will be the inverse of the function applied by the first amplifier. Thus, the gain g_{m1} multiplied by the gain g_{m2} substantially equals a constant. This product of the gains is kept constant by the inverting amplifier **148**.

The output of the second amplifier **144** is applied between an output terminal **146** and the ground line **142**. The capacitors **138, 150**, respectively, provide AC bypassing of the feedback taken from load resistors **136, 146**, allowing full DC feedback with substantially open loop AC performance for the amplifiers **132** and **144**.

The detector filter capacitor **140** of the compression circuit **128** smooths out the sharp spikes in the output of the threshold detector **134** so that the control voltage (V_c) and thus the gain changes smoothly to prevent the excessive distortion of the signal being amplified. This capacitor also defines the attack time constant and, in conjunction with the resistor **141**, defines the release time constant of gain change.

The use of a single threshold detector **48** and detector filter capacitor **140** provides very good input/output transient characteristics during release periods, since the gains of the input and output amplifiers **132, 144** change substantially simultaneously. The system **51** further provides good transient performance during the attack periods.

Differential Voltage Controlled Exponential Current Source (within, e.g., Input Current Controlled Amplifier Control **52**, Main CCA Control **68**, and Clipper **74**)

An exponential current source **148** shown in FIG. **23** provides means for differentially combining voltages and producing an exponentially related current output. This current is also linearly related to an input current. The current source **148** may be used as a building block to produce complex control functions.

For example, the main current controlled amplifier control **68** combines various control functions to provide a single gain control current to main current controlled amplifier **66** which is exponentially related to a combination of control voltages.

The current source **148** includes a first transistor **161**, output transistor **163**, and a feedback transistor **156**.

The first transistor **161**, in the form of a NPN transistor with a collector **158**, base **160**, and emitter **162**, receives the input current, I_{in}, as shown in FIG. **23**, which is then directed to the feedback transistor **156**. By receiving the input current, the first transistor **161** has a base to emitter voltage given by:

$$V_{be1} = V_T \ln\left(\frac{I_{in}}{I_s}\right)$$

where I_s is the saturation of the transistor.

The output transistor **163** is also in the form of an NPN transistor having a collector **164**, base **166**, and emitter **168**. The emitters **162, 168** of the first and output transistors **161, 163** are interconnected. Accordingly, the first and output transistors **161, 163** form a differential pair.

The feedback transistor **156** is an NPN transistor having a collector **172**, base **174**, and emitter **176**. The base of the feedback transistor is interconnected to the collector **158** of the first transistor **161**. The collector **172** of the feeback transistor **156** is interconnected to the emitters **162, 168** of the first and output transistors **161, 162** as shown. A control voltage (V_{in}) is applied between the two bases **160, 166** of the first and output transistors **161, 162.**

Input current (I_{in}) flowing through the collector **158** of the first transistor **161** (minus the small base current of the feedback transistor **156**) necessarily flows into the collector **172** of the feedback transistor **156**. The feedback transistor **156** regulates the base to emitter voltage of the first transistor **161** such that the collector current of the first transistor substantially equals the input current. Linear changes in the difference in the voltage between the first and second bases **160, 166** necessarily implies that the current through the collector **164** (I_{out}) and emitter **168** of the output transistor **163** must change exponentially. The feedback transistor collector **172**

also absorbs the current from the emitter **168** of the output transistor **163**.

X is the ratio of the area of the emitter **168** of the output transistor **163** divided by the area of the emitter **162** of the first transistor **161**.

In the preferred embodiment, the current source **148** is formed on a single integrated circuit. The first and output transistors **161, 163** may accordingly have emitter areas of predetermined ratios. Thus, the output current is given by the following formula:

$$I_{out} = I_{in}\left[\exp\left(\frac{V_{be2} - V_{be1}}{V_T}\right)\right]X$$

where V_{be2} is the voltage between the base **166** and emitter **168** of the output transistor **163**, V_{be1} is the voltage between the base **160** and emitter **162** of the first transistor **161**, and X is the ratio of the area of the emitter **168** of the output transistor **163** divided by the area of the emitter **162** of the first transistor **161**.

The current source **158** provides an exponential change in output current for a linear change in voltage between the base **160** of the first transistor **161** and the base **166** of the output transistor **163**. The current source **148** may be used to provide the input current for additional current sources like the current source **148**, thus allowing the combination of more than two voltages to exponentially control an output current. Such an arrangement may thus be used to control the gain of the main current controlled amplifier **66**. The current source **148** may also be applied in many other hearing aid applications, since a "perceived" linear increase in ∫loudness" requires a substantially exponential increase in amplitude of the sound. Thus, with the present invention, by turning a linear potentiometer, the user of a hearing aid may achieve an apparent linear change in volume (and an exponential change in amplitude).

In addition, the present embodiment of applicant's invention includes only a limited number of components, thus making the circuit more compact. Moreover, the current source **148** may operate with a very low supply voltage, such as one volt.

Regulator with Variable Reference Voltage Outputs (within, e.g., the Highpass and Lowpass Corner Controls **58, 60**)

A regulator **218** provides a pair of constant reference voltages at first and second output terminals **282, 284**. See FIG. **24**. The reference **218** also includes a variable V_{Bout} voltage reference output terminal **280** which may be used to supply a base to emitter voltage over a predetermined range between the above-mentioned pair of reference voltages to a string of transistors used as current sources. Such a regulator **218** may be used, for example, to accurately control the currents I_{X1}, I_{X2}, I_{X3}, I_{X4} supplied by the highpass and lowpass corner control circuit shown in FIG. **18** to the highpass and lowpass filters **54, 56**.

In particular, on integrated circuits it is often important to bias one or series of bases of transistors such that the collector current of each transistor is of a desired magnitude. In order to achieve this, a reference transistor is provided which draws a predetermined current. The same base to emitter voltage necessary to drive this reference transistor may then be used to supply the proper base to emitter voltage, so that a similar current will be drawn by other similar transistors.

As shown in FIG. **24**, the regulator **218** includes first and second top transistors **220, 222**, first and second non-inverting amplifiers **224, 226**, first and second bottom transistors **228, 230**, a potentiometer having an end-to-end resistance of (R_{set}) **232**, and a current reference transistor **234**. The first and second top transistors **220, 222**, in the form of PNP transistors, are interconnected as shown in FIG. **24**.

The transistors **220, 222** include collectors **236, 238**, interconnected bases, **240, 242**, and interconnected emitters **244, 246**. The first amplifier **224** includes positive and negative inputs **248, 250** and an output **252**. The output **252** is interconnected to the bases **240, 242** of the two transistors **220, 222** to drive them in a similar manner.

The first and second top transistors **220, 222**, in the most preferred embodiment, are formed on a single chip. Thus, they have geometries which are closely controlled, and the area of the emitter **246** of the second top transistor **222** is "X" times larger than the area of the emitter **244** of the first top transistor **220**. In the most preferred embodiment used by applicant, X equals 3.

The current traveling through the collector **236** of the first top transistor **220** is designated I_p. As shown in FIG. **24**, the current going through the collector **238** of the second top transistor **222** is equal to $(X)(I_p)$.

The first and second bottom transistors **228, 230** each include a collector **260, 262**, base **264, 266**, and interconnected emitters **268, 270**. The area of the emitter **270** of the second bottom transistor **230** is "Y" times larger than the area of the emitter **268** of the first bottom transistor **228**. In the most preferred embodiment used by applicant, Y equals 2. The collectors **260, 262**, of the first and second bottom transistors **228, 230** are respectively interconnected to the collectors **238, 236** of the second and first top transistors.

The voltage at the collector **236** of the first top transistor **220** is interconnected to the positive input **248** of the first amplifier **224**, and a reference voltage biases the negative input **250** of the first amplifier **224**. Thus, the first amplifier **224** completes a feedback loop between collector **236** and the base **240** of transistor **220** to insure that the current through the collector **236** of the first top transistor **220** (designated I_p) substantially equals the current through the second bottom transistor **230** (designated I_{n2}).

The second amplifier **226** includes positive and negative inputs **254, 256** and an output **258** which drives the first output terminal **282**. The collector **260** of the first bottom transistor **228** is interconnected to the positive input **254**, and a reference voltage biases the negative input to the second amplifier **226**. The output **258** is then interconnected to drive the bases **264, 274** of the first bottom transistor **228** and the reference transistor **234** which will both have a base to emitter voltage of V_{BE1}. Thus, the second amplifier completes a feedback loop between the collector **260** and base **264** of transistor **228** to insure that the collector current (I_{n1}) of transistor **228** substantially equals the collector current (XI_p) of the second top transistor **222**. Therefore $I_{n1}/I_{n2}=XI_p/I_p=X$

The current reference transistor **234** includes collector **272**, base **274**, and emitter **276**, interconnected as shown. The ratio of the area of emitter **276** to the area of the emitter **268** of the first bottom transistor **228** is Z (in the preferred embodiment shown, Z=2). Therefore, the collector current of reference transistor **234** is substantially equal to $ZI_{n1}=2I_{n1}$. Z, of course, can be

chosen to accommodate a variety of end-to-end resistances for the potentiometer **232**.

A potentiometer **232**, with ends interconnected between the first and second output terminals **282, 284**, has a wiper arm **278** interconnected to terminal **280** (V_{Bout}).

The voltage (V_{be2}) between the collector **272** and emitter **276** of the current source transistor **234** is provided to drive the base **266** of the second bottom transistor **230**, and is also available at the second output terminal **284**.

$I_{n1}/I_{n2}=X$ can be satisfied only when:

$$V_{be1}-V_{be2}=V_T \ln(XY)$$

where V_{be1} and V_{be2} are, respectively, the base to emitter voltages of the first and second bottom transistors **228, 230**. Since the ends of potentiometer **232** are interconnected between the base **264** and the base **270**,

$$V_{be1}-V_{be2}=R_{set}(Z\ I_{n1}).$$

Therefore,

$$R_{set}(I_{n1}) = \frac{V_T \ln (XY)}{Z}$$

Accordingly, the voltage (V_{Bout}) at the output terminal **280** on the wiper of the potentiometer **232** may be adjusted over a range of values. The top, highest value is equal to the output voltage at the first output terminal **282**, and is also equal to V_{be1} which is sufficient to drive the first bottom transistor **228** to have the current I_{n1} through it. This same output voltage is therefore also sufficient to make other similar (referred to as a "slave") transistors (i.e., having the same emitter area) elsewhere in the hearing aid circuit **20** draw this current.

When the wiper of the potentiometer **232** is moved downward to its lowest setting, toward the current reference transistor **234**, the voltage on the wiper is equal to the voltage (V_{be2}) at the second output terminal **284** which is supplied to the base **266** of the second bottom transistor **230**, which is sufficient to cause the above slave transistor to draw a current of

$$\frac{I_{n1}}{(X)\ (Y)}$$

In the preferred embodiment X=3 and Y=2, so that varying the wiper of the potentiometer **232** allows a base to emitter voltage sufficient to drive a slave transistor such that it will have a current between I_{n1} and $I_{n1}/6$.

Control over the voltage of the output lead (V_{Bout}) **280** thus allows substantially tight control over the current drawn by any other similar transistor whose base is interconnected to the output lead **280** and whose emitter is interconnected to the ground line **286**. The current regulator **218** allows the reference current (In_1) to be set with only the end-to-end resistance of potentiometer **232**, minimizing the number of bulky and space-consuming resistors that must be used.

Moreover, there is a precisely defined range of adjustment, which is defined simply by the transistor geometries. Of course, additional transistors could have their base emitter junctions placed in parallel with that of the slave transistor in order to drive additional current sources. The slaved transistors may also have independently predetermined emitter area ratios to provide a variety of different currents all adjustable over a range spanning a ratio equal to X times Y. Additional potentiometers may be placed in parallel with potentiometer **232** (their parallel value equalling R_{set}) to provide simultaneous, independently adjstable outputs over the same voltage range as before.

The placement of the first amplifier **224** driving the first and second top transistors **220, 222** makes the current reference **218** substantially insensitive to the current gain characteristics ("betas") of the first and second top transistors **220, 222**. This is advantageous in light of the typically low, loose-tolerance beta of PNP transistors in the usual integrated circuit.

Additionally, since the current I_p is also regulated, "slaved" PNP transistors may be biased from the voltage developed from base **240** to emitter **244** of the first top transistor **220** to supply currents related to I_p by the emitter area ratio between transistor **220** and the slaved PNP transistors.

Detailed embodiments of the first and second amplifiers **224, 226** are shown in FIGS. **24***a* and **24***b*, respectively. It should be noted that differential input amplifiers, as shown in FIG. **24**, are not essential to proper operation (in this case V_{ref} can be thought of as "ground") and that the detailed amplifiers shown allow operation with very low supply voltages (substantially as low as 1 volt).

Current Controlled Clipper **74**

As shown in FIGS. **2** and **26**, the clipper **74** receives an input signal and provides an output signal of a substantially predetermined maximum amplitude. Accordingly, the aid is substantially prevented from producing an uncomfortably loud signal for the hearing aid wearer.

In the preferred embodiment, the clipper **74** includes first and second differential operational transconductance amplifiers **282, 284**, an input terminal **288**, voltage reference line **290** (approximately 0.8 volt for the embodiment shown), output terminal **292**, load resistance **293**, auxiliary output terminal **295**, and adjustable current source **297**.

The first and second transconductance amplifiers **282, 284**, each include a first positive input **294, 296**, a second negative input **300, 302**, and an output **306, 308**. The positive input **294** of the first transconductance amplifier **282** is interconnected to the input terminal **288**, and receives an input signal from the main current controlled amplifier **66**. The negative input **300** is interconnected to the output terminal **292** and the output **308** of the second transconductance amplifier **284**. The output **306** of the first transconductance amplifier **282** is interconnected to the positive input **296** of the second transductance amplifier **284**. The negative input **302** is interconnected to the reference line **290**.

The second transductance amplifier **284** is a standard operational transductance amplifier, as shown in FIG. **22**, with the adjustable current source **297** interconnected to control the transductance (gm_2). The magnitude of the current supplied by the current source **297** sets the peak value of the current (I_L) that the second transductance amplifier **284** can deliver to the load resistance **293** and therefore the voltage clipping level for the output **292** of the clipper **74**.

The current source **297** is included as a part of the output control **90** shown in FIG. **1**. With a substantially high loop gain, (ie., large amount of feedback) the overall voltage gain change of the clipper **74** will be substantially small as the current control is changed.

The preferred embodiment of the second amplifier **284** includes a bipolar transistor differential pair. The open loop gain of the circuit does tend to remain fairly constant as the controlled current supplied to the gain terminal of the second amplifier **284** is varied. This occurs because the input impedance of the second amplifier **284** varies substantially inversely with the control current.

Since this impedance is the most predominant load on the first amplifier **282**, the voltage gain of the first amplifier will change approximately proportionally to this impedance, and approximately inversely to the voltage gain in the second amplifier **284**. As a result, the circuit **74** gives a fairly constant open loop voltage gain. Thus, the present circuit provides a symmetrical, adjustable voltage limiting (clipping) while maintaining a substantially constant voltage gain (substantially independent of supply voltage).

The clipping level set by the device will not be substantially related to or substantially influenced by the saturation voltage drop of the transistors in the clipper **74** or the power supply voltage. Moreover, the clipper **74** operates at a low supply voltage level such as one volt.

The voltage across the input terminals **296, 302** of the second amplifier **284** is referred to hereafter in this section as ΔV_{be}. A given ΔV_{be} will always produce a fixed ratio between the two collector currents in a bipolar transistor differential pair independent of the amplification factor (gm_2) selected for the second amplifier **284**. Accordingly, the ratio of the current through the load resistor **293** to the peak available load current (or clipping level) is dependent substantially on ΔV_{be}.

This voltage ΔV_{be}) may also be useful in other applications and is made available at an auxiliary output terminal **295**. The equation expressing the ratio of current delivered to the load resistor **293** (I_L) to the peak available load current (I_{PEAK}) in terms of V_{be} is as follows:

$$\frac{I_L}{I_{PEAK}} = \tanh\left(\frac{\Delta V_{be}}{2V_T}\right)$$

In the present invention, V_{be} is used to drive the AGC detector **86** for the output compression system. The detector **86** is in the form of the threshold detector shown in FIG. **20** and has a voltage detection threshold of approximately 18 mV. Therefore, the output AGC system may be activated when

$$\frac{I_L}{I_{PEAK}} \approx \tanh\left(\frac{18\text{ mV}}{2\,(26\text{ mV})}\right) = .333$$

which (when expressed in decibels) is approximately −9.6 dB. This means that a signal level which is about −9.6 dB relative to the signal level at which clipping begins will begin to activate the output compression when the external AGC switch **88** is turned on. (See FIG. **2**).

In such an application, the output compression level tracks below the voltage clipping level described above by a fixed ratio. In this manner, the "overshoot" during the automatic gain control attack is limited to a fixed ratio relative to the steady state output during compression and the output control **90** will also function when output AGC operation is selected.

Voltage Clamp (within, e.g., the Output Amplifier **76**)

Dropping the voltage of a collector of a transistor on the integrated circuit even by an amount approaching one junction drop (0.6 Volts) below the lowest chip potential (that of the substrate) can have disasterous performance effects for the entire chip, because electrical isolation to surrounding chip components is lost, creating an undefined operating condition. A voltage clamp **314** prevents voltage swings at a node in an integrated circuit from going substantially negative with respect to the substrate and causing undesired operation. See FIG. **27**.

Thus, for example, the receiver **40** of the present invention includes a center tapped inductor **316** which exerts a magnetic field to move the diaphram to create an acoustic output to the hearing aid user. The receiver **40** thus presents an inductive load, to the output amplifier **76** which drives it.

A mutual inductance between the two halves of the center tapped inductor **316** can result in a negative collector to emitter voltage spike alternately on one or the other of the output transistors **318, 320** which drive the receiver **40**. In turn, this can forward bias the collector to substrate junction **322**, causing parasitic lateral transistor action to surrounding devices.

In order to avoid such an occurance of unpredictable behavior in surrounding devices, the present hearing aid circuit **20** includes the clamp **314** in the output amplifier **36**. The clamp **314** includes first and second voltage sensing transistors **324, 326**, in the form of NPN transistors, a reference voltage source **328**, including a biased diode connected NPN transistor **329**, and an amplified current mirror **330**.

In the preferred embodiment shown in FIG. **27**, the receiver **40** is shown having the center tap inductor **316** interconnected to the first and second output transistors **318, 320**, each of which has a collector **336, 338**. The collectors **336, 338** are interconnected to the inductor **316** at respective nodes **340, 342**. The clamp **314** prevents the voltage at the nodes **340, 342** from dropping substantially below zero.

The first and second output transistors **318, 320** have emitters directly connected to the substrate **322** of the chip. The reference voltage source **328** includes an NPN diode connected transistor **329** having a base **345** interconnected to a collector **344** and emitter **346**. The emitter **346** is interconnected to the substrate **322**. The collector **344** is interconnected to the bases of the first and second voltage sensing transistors **324, 326**.

The collectors **336, 338** of the first and second output transistors **318, 320** are interconnected respectively to the emitters **325, 327** of transistors **324, 326**. When both the collectors **336, 338** have voltages which are substantially above zero, the base-emitter junctions of transistors **324, 326** will be reverse biased or, at most, only slightly forward biased. Consequently, the reference voltage source **328** retains the first and second voltage sensing transistors **324, 326** in substantially a non-current drawing, nonconductive state.

As the voltage at one of the nodes **340, 342** drops near zero, the base to emitter voltages (V_{be1}, V_{be2}), respectively, for the first or second transistors **324, 326** increases to about 0.6 volt, turning that first or second transistors **324, 326** on to a conductive state, thereby drawing a current (I_{sense}) through collector **331** or col-

lector **333** (which are interconnected) of transistors **324** or **326**. I_{sense} is given by:

$$I_{sense}=I_o[\exp(V_{be1}/V_T)+\exp(V_{be2}/V_T)]$$

The amplified current mirror consists of transistors **348, 350, 352**. The dual collector PNP transistor **348** is connected as a conventional current mirror to receive I_{sense} and mirror this current to the interconnected bases of the first and second high current transistors **350, 352**, which can amplify I_{sense}. Upon sensing that the collector to emitter voltages at the first or second voltage sensing transistors **324, 326** drops near zero, the dual collector PNP transistor **348** turns on supplying current to the bases of the two high current tranisistors **350, 352**. The high current transistors **350, 352** then directly supply currents (I_{clamp1} and I_{clamp2}) to the nodes **340, 342**.

Two negative feedback loops are formed in the clamp **314**. The first is formed by transistors **324, 348, 350**, with the emitter **325** being the input and the emitter of high current transistor **350** being the output. The second loop is formed by transistors **326, 348** and **352** with the emitter **327** being the input and the emitter of high current transistor **352** being the output. Even though both loops could operate simultaneously if both nodes were forced near zero volts, and both loops share PNP transistor **348**, the application of the preferred embodiment requires that only one node be clamped at a time, since the output transistors alternate conduction states. The bases of transistors **350, 352** are interconnected. Consequently, the ratio of currents delivered by the emitters of these transistors to nodes **340, 342** is dependent on the difference in voltage between these two nodes (V_{diff}) as follows:

$$I_{clamp1}/I_{clamp2}=\exp(V_{diff}/V_T).$$

Since V_{diff} is typically greater than 2 volts when one node is being clamped, the high current transistor **350** or **352** connected to the other node is effectively turned off.

The node being clamped receives as much current (up to the limit I_{max} described below) as is required to prevent the node from going substantially negative with respect to the substrate. As long as the current ratings of current source transistors **350, 352** are not exceeded, the maximum current (I_{max}) which can be supplied to the nodes **340, 342** is approximately equal to:

$$(\beta)^2(I_{ref})$$

where β (beta) is the current gain of the transistors **324, 326, 350, 352** and I_{ref} is the current through the resistor **354** (which is also the standby current of the clamp **314**).

Since a typical β could be 100 or higher, the described clamp **314** uses a very low standby current drain relative to the maximum current sourcing ability of the clamp **314**. Moreover, the clamping action occurs very close to the lowest potential supplied to the circuit. In addition, the clamp **314** may operate with a low supply voltage such as 1 volt.

The present clamp **314**, with or without the amplified current mirror **330**, may also be used simply to detect voltage levels close to the lowest (or highest if circuit polarities are inverted) supply potential, where I_{sense} becomes a detection signal. In one such application, the amplified current mirror **330** is removed from the circuit, and the reference voltage source **328** is changed to a 0.9 volt source. Thus, the modified circuit may be used to detect output voltage and perform the function of the "V_{out} detector" **80** shown in FIG. **2** for the output automatic gain control circuit contained within "output amplifier, clipper and output AGC" **36** of FIG. **2**.

Base Bias Current Compensation Circuit (within, e.g., the Input Current Controlled Amplifier **46** and Main Current Controlled Amplifier **66**)

It is often necessary to reduce the loading effect which the base bias current of a transistor has upon the circuit which drives the base of the transistor. As shown in FIG. **28**, a base bias current compensator **358** supplies approximately the base bias current requirements of a reference transistor **362** which would otherwise have to be supplied by the other circuitry associated with the base of the reference transistor. The reference transistor is carrying an approximately known reference current (I_c) through its collector and has a beta (or current gain) which is known to track or match well with another transistor. This is usually the case in a given integrated circuit.

As shown in FIG. **28**, the compensator **358** includes a current source **360** and a reference transistor **362**, as well as a sampling transistor **364**, first and second mirror transistors **368, 366** and feedback transistor **370**. The most preferred embodiment also includes a diode connected transistor **372**, an additional mirror transistor **374**, and an additional reference transistor **376**.

In the preferred embodiment, the transistors all are formed on the same integrated circuit chip. Thus, the emitter areas, current gain characteristics, and the transconductance characteristics of the NPN transistors may be fairly substantially controlled so that they bear a predetermined relation toward each other. The same holds true for PNP transistors, although the relationship between NPN and PNP characteristics is not well determined.

The reference transistor **362** handles a substantially known collector to emitter reference current, now designated I_c in FIG. **28**. A base current of I_b, which is equal to I_c/B_{ref} (where B_{ref} is the current gain of transistor **362**), must be provided to the reference transistor **362** so as to substantially cancel the bias current that would be otherwise supplied by other circuitry associated with the base of transistor **362**.

The current source **360** provides a current in a substantially known ratio to the reference current, now designated (X) (I_c). The current source **360** supplies most of its current to the sampling transistor **364** (which has a beta approximately equal to B_{ref}. The current supplied to the base of the sampling transistor **364** is approximately equal to (X) (I_B) (assuming that transistors **362** and **364** have approximately equal current gain). Current supplied to the base of the sampling transistor **364** is supplied by the collector of the first mirror transistor **368**.

The feedback transistor **370** (interconnected as shown in FIG. **28**) substantially forms a differential pair with the sampling transistor **364** and serves to adjust the collector current of the first mirror transistor **368** so as to regulate the collector current of the sampling transistor **364** to be approximately equal to XIc minus the collector current (I_{FB}) of feedback transistor **370**. The base of transistor **370** is biased by a reference voltage V_{ref} as shown in FIG. **28**.

The diode connected transistor **372** which is in parallel with the base-emitter junction of first mirror transistor **368** is included in the preferred embodiment in order

to reduce the effect of PNP beta (current gain) variation on I_{FB}. For the embodiment shown, I_{FB} is approximately equal to XI_B. Therefore, since XI_c/XI_B is approximately the current gain of the sampling transistor **364**, the current source **360** will supply

$$XI_c - \frac{XI_c}{B}$$

or XI_c $(1-1/\beta)$ to the sampling transistor **364**. For typical betas, $(1-1/\beta)$ can be very close to unity.

The second mirror transistor **366** has its base and emitter interconnected respectively to the base and emitter of the first mirror transistor **368**. By scaling the emitter areas of the first and second mirror transistors **368, 366** the current through the second mirror transistor **366** may be set to be in a predetermined ratio to the current through the collector of the first mirror transistor **368**. This predetermined ratio may be set equal to 1/X. Since the current through the collector of the first mirror transistor **368** approximately equals (X) (I_B), the current through the collector of the second mirror transistor **366** approximately equals (X) (I_B) divided by X or I_B, which is approximately the desired base current for the reference transistor **362**.

One or more additional mirror transistors (such as the transistor **374**) may have its base-emitter junction placed in parallel with the base-emitter junction of the first and second mirror transistors **368, 366**. Thus, additional reference transistors, such as the transistor **376**, may have their base current requirements supplied as well.

By varying the ratio X and the ratios of the emitter areas of the mirror transistors, base compensation currents of arbitrary ratios are possible. The present application provides a very wide variety of applications where approximate cancellation of or compensation for base currents is required. Moreover, the compensator **358** operates at a very low supply voltage, such as one volt.

Input Automatic Gain Control System **600**

A more detailed diagram of the input Automatic Gain Control ("AGC") system **600** is shown in FIG. **29**. Certain circuit elements from FIG. **2** have been redrawn and renumbered in FIG. **29** as an aid for instruction.

The primary signal path is through the primary Current Controlled Amplifier ("CCA") **602**. The primary CCA **602** is loaded by resistor R_{LP} **630** and has full DC feedback taken from the junction of R_{LP} **630** and capacitor **634**. The capacitor **634** effectively bypasses AC feedback, providing substantially open loop AC operation.

Components **602, 630, 634** are contained in FIG. **2** as the main CCA **66**. The balance of the circuit, shown in dotted lines **604**, develops the primary control current (I_{pc}) for the primary CCA **602**. The differential voltage controlled exponential current sources **612, 624, 626**, designated Exp in FIG. **29**, is shown in FIG. **23** and, as previously discussed, provides an output current (I_{out}) related to an input current (I_{in}) and control voltage (V_c) according to the following equation:

$$I_{out} = I_{in}\left[\exp\left(\frac{\Delta V_c}{V_T}\right)\right]x$$

where x is the emitter area ratio previously discussed, and $V_c = V_{be2} - V_{be1}$.

The current controlled amplifiers **602, 606** are operational transconductance amplifiers (OTAs), as previously discussed and shown in FIG. **22**. The secondary CCA **606** is loaded by resistor R_{LS} **632** and has full DC feedback taken from the junction of R_{LS} **632** and capacitor **636**. The capacitor **636** effectively bypasses AC feedback, providing substantially open loop AC operation. Components **606, 632, 636** are contained in FIG. **2** as the secondary CCA **700**.

The input signal (V_{in}) (which in FIG. **2** comes from the variable slope control **64**) is also amplified by the secondary CCA **606** whose output voltage developed across R_{LS} **632** is applied to a threshold detector **702** consisting of the detector circuit shown in FIG. **20**. The output of detector **702** is smoothed by the AGC filter capacitor **704** to develop a control signal V_{c1}.

The control signal, which is developed and measured with respect to a voltage reference V_{ref}, is fed back, via the exponential current source **612**, as a secondary control current (I_{sc}) for the secondary CCA **606**. If the input signal level is very low, then even when amplified by the secondary CCA **606**, the signal level will be below the threshold of the threshold detector **608** and the control signal ΔV_{c1} will be zero.

Under this circumstance, the voltage across AGC filter capacitor **704** is kept at approximately V_{ref} by the series resistor string made up of R_{limit} **622** and the compression ratio control (CR) **620**, interconnected between the output of the detector **702** and V_{ref}.

The gain A_s of the secondary CCA **606** is determined by the current (I_{sc}) applied to its gain control input **642**. The gain A_s when $\Delta V_{c1}=0$ is defined as A_{so}.

The current out of Exp_1 **624** (I_{th}) (which is the input current to Exp_2) is:

$$I_{th} = [I_{sref}x_1]\left[\exp\left(\frac{k_2\Delta V_{c2}}{V_T}\right)\right]$$

where k_2 V_{c2} is the voltage at the wiper arm **638** of potentiometer **616**, having a total resistance R_{thresh} whose end terminals are interconnected to V_{ref} and fixed current source **618** having a value I_{thresh}. Therefore $k_2\Delta V_{c2}$ may be varied by potentiometer **616** from zero volts to $V_{c2}=I_{thresh}$ times R_{thresh} (as K_2 is varied from 0 to 1). X_1 is the emitter area ratio constant for current source Exp_1 **624**, and I_{sref} is supplied by fixed current source **628**.

The current out of Exp_2 **612** (I_{sc}) (which is the control current for the secondary CCA **606**) is:

$$I_{sc} = [I_{th}][x_2]\exp\left(\frac{\Delta V_{c1}}{V_T}\right)$$

where x_2 is the emitter area ratio constant for current source Exp_2 **612**. Thus

$$I_{sc} = I_{sref}(x_1)(x_2)\left[\exp\left(\frac{\Delta V_{c1} + k_2\Delta V_{c2}}{V_T}\right)\right]$$

Thus, when ΔV_{c1} is zero (signal level below the AGC threshold),

$$I_{sc} = [I_{sref}(x_1)(x_2)]\left[\exp\left(\frac{\Delta V_{c2}}{V_T}\right)\right]$$

and varying the setting of the threshold control **616** varies the gain A_{so} of the secondary CCA and thus the amplitude of V_{in} required to trigger the threshold detector.

The threshold V_{th} of the threshold detector **702** is reached when $A_{so}\,V_{in}=V_{th}$. This occurs when

$$V_{in} = \left[\frac{V_{th}}{A_{so}}\right]\left[\frac{1}{\exp\left(\frac{K_2\Delta V_{c2}}{V_T}\right)}\right]$$

Accordingly, the threshold is adjusted in an exponential manner by K_2, the setting of the threshold control **616**.

When the threshold is exceeded the threshold detector **702** discharges filter capacitor **704** and V_{c1} decreases from zero, decreasing the gain (A_s) of the secondary CCA **606**. This forms a feedback system, and with high loop gain, the system will keep the output of the secondary CCA **606** very close the detector threshold V_{th}. Then, for input levels above the threshold point,

$$A_s(V_{in}) = [A_{so}(V_{in})]\left[\exp\left(\frac{\Delta V_{c1}}{V_T}\right)\right] \approx V_{th}.$$

An adjustable portion ($K_1\Delta V_{c1}$) of the control signal ΔV_{c1} taken from the wiper arm **640** of the compression ratio control (potentiometer) **620** is used as a feedforward signal to control the gain of the primary CCA **602**. K_1 varies from 0 to 1 (or to some other preselected limit less than 1 determined by R_{limit} **622**) by adjustment of the control **620**. $K_1\Delta V_{c1}$ is applied to the voltage inputs of current source Exp_3 **626** and I_{pref} from fixed current source **614** is the current input to Exp_3. The output current from Exp_3, designated I_{pc} (which is applied to the gain control terminal **644** of the primary CCA **602**) is given by:

$$I_{pc} = [I_{pref}(X_3)]\left[\exp\left(\frac{K_1\Delta V_{c1}}{V_T}\right)\right]$$

where x_3 is the emitter area ratio constant for current source Exp_3 **626**.

The gain A_p of the primary CCA **602** is given by

$$A_p = [(A_{po})][\exp(K_1\Delta V_{c1}/V_T)]$$

Below the threshold, $V_{c1}=0$ and the CCA **602** has a fixed gain A_{po}. Above the threshold, the gain is given by:

$$A_p = A_{po}\left[\exp\left(\frac{\Delta V_{c1}}{V_T}\right)\right]^{K1} = (A_{po})\,[V_{th}/(V_{in}A_{so})]^{K1}$$

The output signal is $V_{out}=(A_{po})\,(V_{in})$. Expressed in decibels, where L is the amplitude in (dB) and G is the gain in (dB), $L_{in}=20\log(V_{in})$; $L_{out}=20\log(V_{out})$, and $G_{po}=20\log(A_{po})$. Below threshold, $L_{out}=L_{in}+G_{po}$. Above threshold,

$$L_{out}=G_{po}+L_{inth}+(1-K_1)(L_{in}-L_{inth})$$

where L_{inth} is the input level corresponding to threshold and is given by

$$L_{inth} = 20\log(V_{th}/A_{so}) = 20\log\left\{V_{in}\left[\exp\left(\frac{K_2\Delta V_{c2}}{V_T}\right)\right]\right\}$$

These characteristics are illustrated in the output versus input curve shown in FIG. **30**.

Also, in the preferred emobidment, the base bias compensation circuits, as shown in FIG. **28** and previously discussed, are interconnected to the positive and negative inputs of the primary and secondary CCA's **602**, **606** and substantially supply their input base current requirements. This reduces feedthru of the gain control currents I_{pc}, I_{sc} into the signal paths of the CCAs. Such feedthru may cause undersirable clicks and thumps in the signal as well as cause transient signal amplitude aberrations during the attack and decay periods of AGC operation.

In addition, in the preferred embodiment, the compand control voltage (V_c in FIG. **21**) is applied to the negative input of Exp_2 (**612**) in place of V_{ref} to complete the compansion system and provide a linear input/output relationship between microphone output **22** and detector **702** input.

A variety of preferred embodiments of the present invention have been described herein. It is to be understood, of course, that changes and modifications may be made in embodiments without departing from the true scope and spirit of the present invention, as defined by the appended claims.

What is claimed is:

1. A hearing aid comprising, in combination:
a microphone for receiving an input signal and providing a microphone signal;
a filter for receiving and shaping said microphone signal and providing a filtered signal, said filter including a four pole adjustable corner lowpass filter in cascade with an adjustable slope filter;
an amplifier for receiving said filtered signal and responsively providing an amplified signal; and
a receiver for receiving said amplified signal and responsively providing a sound signal.

2. A hearing aid comprising, in combination:
a microphone for receiving an input signal and providing a microphone signal;
a filter for receiving and shaping said microphone signal and providing a filtered signal, said filter including a four pole adjustable corner lowpass filter in cascade with both a four pole adjustable corner highpass filter and an adjustable slope filter;
an amplifier for receiving said filtered signal and responsively providing an amplified signal; and
a receiver for receiving said amplified signal and responsively providing a sound signal.

3. A hearing aid comprising, in combination:
a microphone for receiving an input signal and providing a microphone signal;
a filter for receiving and shaping said microphone signal and providing a filtered signal, said filter including a four pole adjustable corner highpass filter in cascade with an adjustable slope filter;

an amplifier for receiving said filtered signal and responsively providing an amplified signal; and

a receiver for receiving said amplified signal and responsively providing a sound signal.

4. A hearing aid comprising, in combination:

a microphone for receiving an input signal and providing a microphone signal;

a compression amplifier to compress said microphone signal and provide a compressed signal;

a filter for receiving said compressed signal and providing a filtered signal;

an expansion amplifier for receiving said filtered signal and responsively providing an expanded signal;

a control circuit for operating said compression and expansion circuits inversely, said control circuit including a detector for receiving said compressed signal; and

a receiver for receiving said expanded signal and responsively providing a sound signal.

5. A hearing aid comprising, in combination:

a microphone for receiving an input signal and providing a microphone signal;

an adjustable gain amplifier for recieving said microphone signal and providing an amplified signal;

an adjustable peak clipping circuit for receiving said amplified signal and responsively providing a clipped signal, said peak clipping circuit substantially limiting an instantaneous value of said clipped signal to a predetermined maximun level;

a fixed gain output stage for receiving said clipped signal and providing an output signal; and

a receiver for receiving said output signal and responsively providing a sound signal.

6. A hearing aid comprising, in combination:

a microphone for receiving an input signal and providing a microphone signal;

a volume control for receiving said microphone signal and responsively providing a volume controlled signal;

an adjustable automatic gain control circuit for receiving said volume controlled signal and responsively providing a modified signal;

a fixed gain output stage for receiving said modified signal and providing an output signal; and

a receiver for receiving said output signal and responsively providing a sound signal.

7. A hearing aid comprising, in combination:

a microphone for receiving an input signal and providing a microphone signal;

a volume control for receiving said microphone signal and responsively providing a volume controlled signal;

an adjustable automatic gain control circuit for receiving said volume controlled signal and responsively providing a modified signal;

a fixed gain output stage for receiving said modified signal and providing an output signal;

an auxiliary automatic gain control circuit for detecting the output voltage and output current of said output stage and responsively adjusting said adjustable automatic gain control circuit; and

a receiver for receiving said output signal from said output stage and responsively providing a sound signal.

8. A hearing aid comprising, in combination:

a microphone for receiving an input signal and providing a microphone signal;

an input automatic gain control circuit, including

a primary amplifier for receiving said microphone signal and providing a primary amplified signal in response to said microphone signal and having a variable gain controlled by a primary control signal,

a secondary amplifier for receiving said microphone signal and providing a secondary amplified signal in response to said microphone signal and having a variable gain controlled by a secondary control signal,

a threshold detector for sensing that said secondary amplified signal exceeds a predetermined level and responsively issuing a detected signal,

a variable compression ratio control for receiving said detected signal and responsively providing a portion of said detected signal as said primary control signal to said primary amplifier, and

a variable compression threshold control for providing a threshold control signal, said threshold control signal and said detected signal cooperatively defining said secondary control signal for said secondary amplifier, whereby the compression threshold and compression ratio of said primary amplifier may be independently controlled; and

a receiver for receiving said primary amplified signal and responsively providing a sound signal.

9. A hearing aid as claimed in claim 8, further comprising in combination:

a filter for receiving and shaping the frequency spectrum of said microphone signal and issuing a filtered signal;

wherein said filter is positioned between said microphone and said input automatic gain control system, said input automatic gain control system receiving said filtered signal.

10. A hearing aid comprising, in combination:

a microphone for receiving an input signal and providing a microphone signal;

an input automatic gain control circuit, said input automatic gain control circuit including a detector providing an input gain control signal;

an output automatic gain control circuit, said output automatic gain control circuit including an detector providing an output gain control signal;

a control signal combining network for receiving said input and output gain control signals and responsively providing a secondary control signal; and

a variable gain amplifier for receiving said microphone signal and providing an amplified signal, said amplifier exhibiting a gain and said gain being controlled by said secondary control signal from said control signal combining network; and

a receiver for receiving said amplified signal and responsively providing a sound signal.

11. A hearing aid comprising, in combination:

a microphone for receiving an input signal and providing a microphone signal;

a compansion system, said compansion system including a detector providing a compansion signal;

a variable gain control for providing a variable gain control signal;

a control signal combining network for receiving said compansion signal and said variable gain control signal and responsively providing said secondary control signal;

a variable gain amplifier for receiving said microphone signal and providing an amplified signal,

said amplifier exhibiting a gain and said gain being controlled by said secondary control signal from said control signal combining network; and

a receiver for receiving said amplified signal and responsively providing a sound signal.

12. A hearing aid comprising, in combination:

a microphone for receiving an input signal and providing a microphone signal;

an automatic gain control circuit, said automatic gain control circuit including a gain control detector providing a gain control signal;

a compansion system, said compansion system including a detector providing a compansion signal;

a control signal combining network for receiving said gain control signal and said compansion signal and responsively providing a secondary control signal;

a variable gain amplifier for receiving said microphone signal and providing an amplified signal, said amplifier exhibiting a gain and said gain being controlled by said secondary control signal from said control signal combining network; and

a receiver for receiving said amplified signal and responsively providing a sound signal.

13. A hearing aid comprising, in combination:

a microphone for receiving an input signal and providing a microphone signal;

an automatic gain control circuit, said automatic gain control circuit including a detector for providing an automatic gain control signal;

a variable gain control for providing a variable gain control signal;

a control signal combining network for receiving said automatic gain control signal and said variable gain control signal and responsively providing a secondary control signal;

a variable gain amplifier for receiving said microphone signal and providing an amplified signal, said amplifier exhibiting a gain and said gain being controlled by said secondary control signal from said control signal combining network; and

a receiver for receiving said amplified signal and responsively providing a sound signal.

* * * * *