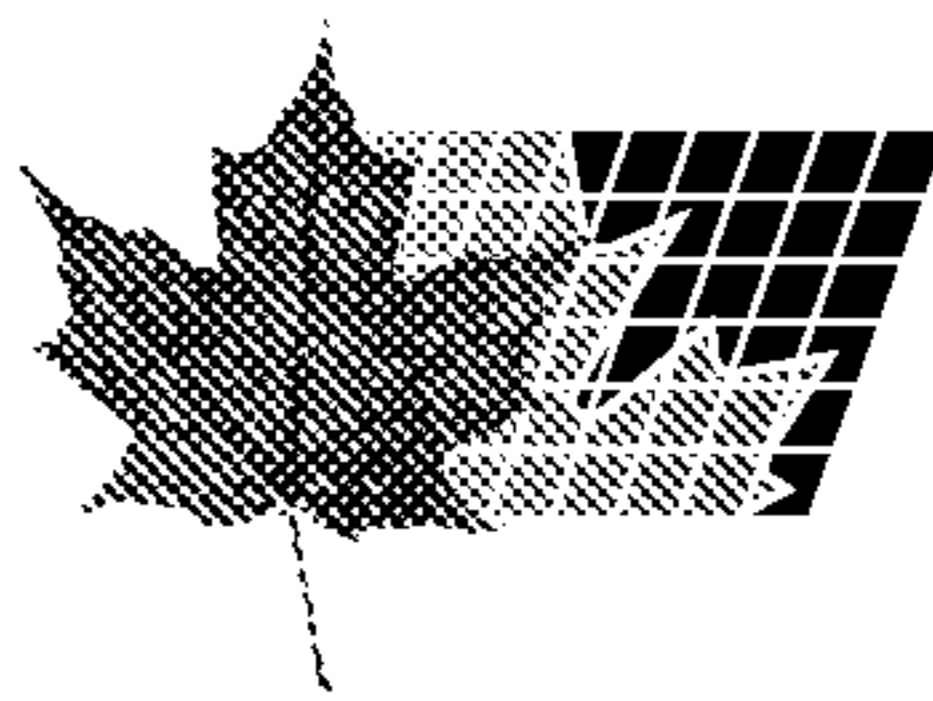




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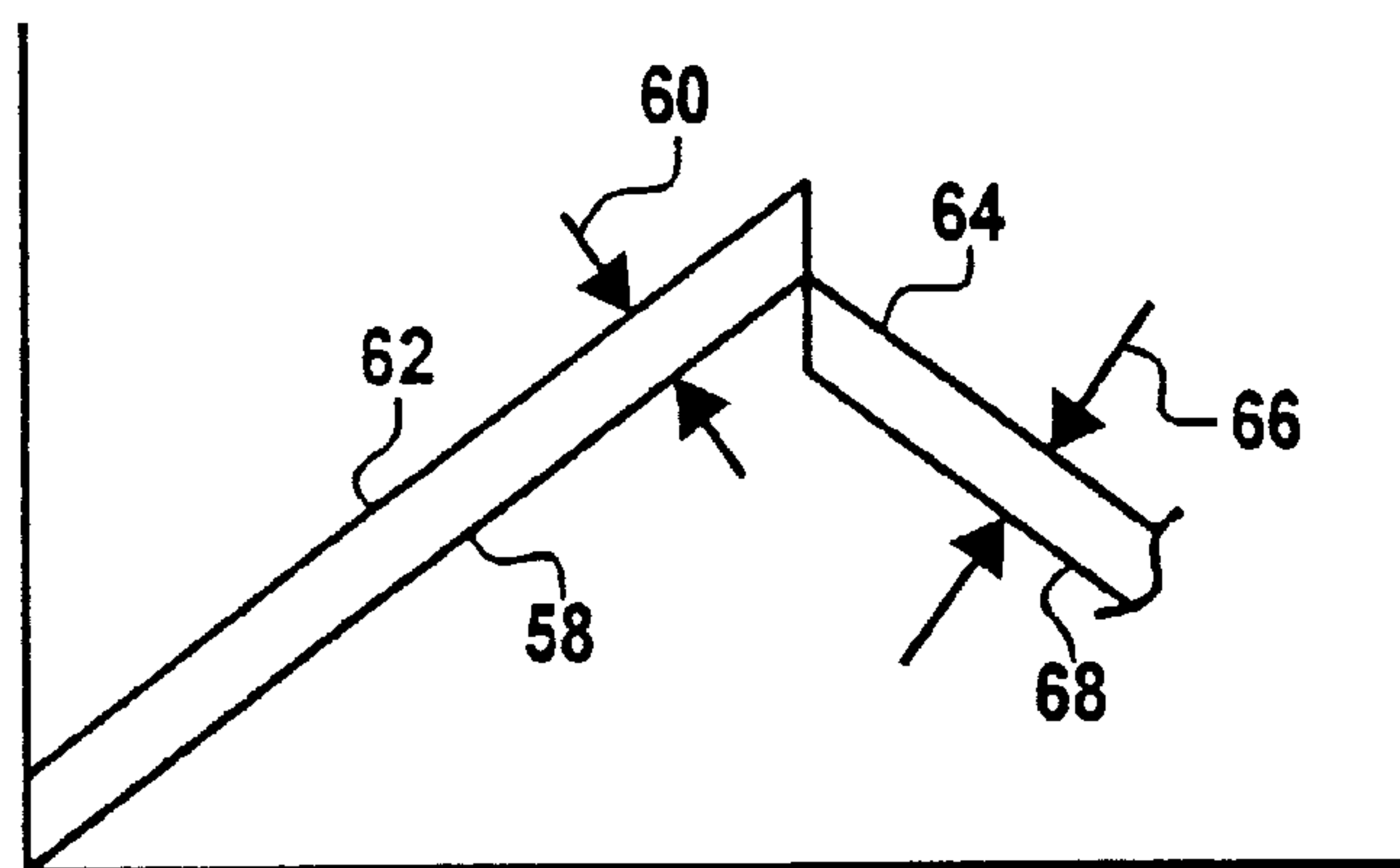
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(54) **SYSTEMES ADAPTATIFS ET UTILISATION AVEC DES
CONVERTISSEURS N/A NON LINEAIRES**

(54) **ADAPTIVE SYSTEMS AND USE WITH NONLINEAR D/A
CONVERTERS**



(57) Adaptive learning systems, such as adaptive frequency-hopping oscillators, recall previously-stored channelizing information for one channel from a RAM, or from both a PROM and a RAM, drive an output frequency of a VCO toward phase lock for that one channel, correct the recalled channelizing information in a parallel adder, drive the output frequency of the VCO closer to phase lock in response to the corrected channelizing information, store the corrected channelizing information in the RAM, and repeat the correcting, driving, and storing steps before recalling channelizing information for an other channel, compensating for all nonlinearities of analog components including the VCO and a D/A converter, and obviating the necessity of inserting housekeeping steps before changing to a new channel. Preferably, a nonlinear D/A converter is substituted for the D/A converter in learning paths of the adaptive frequency-hopping oscillators. Additional adaptive learning systems, such as a digital sample-and-hold device and a digital follow-and-hold device, include a learning path with a nonlinear A/D converter therein that further includes a nonlinear D/A converter with downward steps that provide dual addresses.

ABSTRACT OF THE DISCLOSURE

ADAPTIVE SYSTEMS AND USE WITH NONLINEAR D/A CONVERTERS

Adaptive learning systems, such as adaptive frequency-hopping oscillators, recall previously-stored channelizing information for one channel from a RAM, or from both a PROM and a RAM, drive an output frequency of a VCO toward phase lock for that one channel, correct the recalled channelizing information in a parallel adder, drive the output frequency of the VCO closer to phase lock in response to the corrected channelizing information, store the corrected channelizing information in the RAM, and repeat the correcting, driving, and storing steps before recalling channelizing information for an other channel, compensating for all nonlinearities of analog components including the VCO and a D/A converter, and obviating the necessity of inserting housekeeping steps before changing to a new channel. Preferably, a nonlinear D/A converter is substituted for the D/A converter in learning paths of the adaptive frequency-hopping oscillators. Additional adaptive learning systems, such as a digital sample-and-hold device and a digital follow-and-hold device, include a learning path with a nonlinear A/D converter therein that further includes a nonlinear D/A converter with downward steps that provide dual addresses.

TITLE OF THE INVENTION
ADAPTIVE SYSTEMS AND USE WITH NONLINEAR D/A CONVERTERS

BACKGROUND OF THE INVENTION

Field of the Invention

5 The present invention relates generally to adaptive learning systems and digital-to-analog converters. More particularly, the present invention pertains to adaptive learning systems, such as frequency-hopping oscillators, phase-locked oscillators, digital sample-and-hold devices, digital follow-and-hold devices, and analog-to-digital converters, and to nonlinear digital-to-analog converters that
10 are subcombinations of the adaptive learning systems.

Description of the Related Art

 An adaptive learning system is a system that adaptively corrects, adjusts, or otherwise learns as it operates. Commonly, the learned information is stored digitally, subsequently recalled, D/A converted, used, further
15 corrected, and restored.

 An adaptive learning system, although at least including an electronic system, can be used to adaptively control mechanical and/or hydraulic systems. As an example, frequency-hopping oscillators may adaptively learn to compensate for temperature drift of analog components.

20 Frequency-hopping transmitters are capable of transmitting radio frequencies on successive ones of a plurality of individual output frequencies with the output frequencies chosen in accordance with a code for a particular day or period.

 Since the transmitted information remains on a given frequency for a
25 matter of seconds, or microseconds, and since the order of selection of frequencies can be changed rapidly and precisely, information can be successfully encoded by the use of frequency-hopping transmitters.

 As an example, when used to transmit video signals, a frequency-hopping transmitter could transmit each successive scan line at a different
30 frequency.

 The individual output frequencies are called channels, and the process of dividing a range of frequencies into channels is called channelizing. Each channelized frequency is produced by applying a selective voltage to a voltage-

controlled oscillator (VCO), and the selective voltages that will drive the voltage-controlled oscillator to the channelized frequencies are called channelizing voltages.

Frequency-hopping oscillators can be designed to learn channelizing voltages for a particular voltage-controlled oscillator, to correct for errors of proportionality and nonlinearity of analog components, and to correct for temperature-caused drift of analog components. Learning systems are sometimes called adaptive systems or adaptive learning systems.

Charavit et al., in U.S. Patent 4,511, 858, issued 16 April 1985, teaches embodiments of phase-locked oscillators that use analog integrators. Their phase-locked oscillators are adaptive in that channelizing voltages are stored, recalled, corrected through a phase-locked loop, and placed again in storage.

Hulbert et al., in U.S. Patent 4,810,974, issued 7 March 1989, teaches algebraically summing UP/DOWN signals in a counter which has therein previously stored channelizing information that has been recalled from a random access memory (RAM), correcting the channelizing information for temperature drift, one bit at a time, while driving the output frequency with channelizing information that is held in a latch. That is, corrected channelizing information is developed by counting and subsequently storing in a RAM for use the next time the same frequency is accessed.

A frequency-hopping transmitter is a transmitter that utilizes a frequency-hopping oscillator. In like manner, a frequency-hopping receiver is a receiver that utilizes a frequency-hopping oscillator. A frequency-hopping oscillator is a phase-locked oscillator that is channelized and whose channelized frequencies can be accessed rapidly in response to a predetermined program.

Phase-locked oscillators are used in transmitters for producing an output frequency that is crystal referenced, for demodulating frequency-modulated signals in radio receivers, to achieve frequency-deviation compression in frequency-modulated and phase-modulated receivers, and in various devices in which both rapid change to selected frequencies and precise frequency control are critical.

The use of phase-locked oscillators to achieve frequency-deviation compression in radio receivers is taught by Lautzenhiser in U.S. Patent 5,091,706, issued February 25, 1992; in U.S. Patent 5,497,509, issued March 5, 1996; and in U.S. Patent 5,802,462, issued September 1, 1998.

5 Phase-locked oscillators can be ac modulated, dc modulated, or both, as taught by Lautzenhiser in U.S. Patent 5,091,706; in U.S. Patent 5,097,230, issued March 17, 1992; and in U.S. Patent 5,311,152, issued May 10, 1994. In addition, phase-locked oscillators can be channelized as also taught by the aforesaid Lautzenhiser patents. Frequency-hopping oscillators may be ac and/or
10 dc modulated using principles taught in the aforesaid Lautzenhiser patents.

In phase-locked oscillators, both a forward path and a feedback path are connected to a crystal-controlled reference oscillator by a comparing device. Phase lock is achieved when a feedback frequency from a voltage-controlled oscillator equals the frequency of the reference oscillator.

15 Channelization of phase-locked oscillators is achieved by channelizing the feedback path. The feedback path is channelized by dividing frequencies in the feedback path by N , as shown herein, by any of the ways taught by Lautzenhiser in the aforesaid patents, by partial N manipulation, or by nearly any other method that is conceivable.

20 Since channelization of the feedback path is dependent only upon the time required to divide the frequency in the feedback path by a different number, if a channelization voltage is simultaneously applied to the VCO, channelization is extremely rapid.

25 AC modulation of the forward path, at frequencies above the loop frequency, may be achieved by applying an analog voltage, or modulating voltage, to the VCO via a modulation resistor, as taught in the aforesaid Lautzenhiser patents, or by any other suitable means.

30 DC modulation of the feedback path may be achieved by digital manipulation of pulses in the feedback path, as taught by Lautzenhiser in the aforesaid patents, or by any other suitable means.

In phase-locked oscillators, an error signal is produced by a difference in a feedback frequency to a reference frequency. This error signal may be integrated by analog or digital circuitry.

In phase-locked oscillators that use an analog integrator, the error signal is time integrated. This time-integrated error signal, which is a voltage, is applied to the VCO during the integration process. The error signal disappears and integration stops when phase lock is achieved.

5 In phase-locked oscillators that use a digital integrator, the error signal is integrated by summing clock-timed UP, DOWN, and/or ZERO error signals. D/A conversion changes the digitally integrated error signal into a voltage which is applied to the VCO during the integration process. The error signal disappears and integration stops when phase lock is achieved.

10 BRIEF SUMMARY OF THE INVENTION

The adaptive learning systems of the present invention learn to compensate for variations in proportionality and linearity of analog components, and temperature drift. Adaptive learning functions of some embodiments included herein include storing, recalling, driving, and repeatedly correcting
15 previously corrected information.

In addition to frequency-hopping oscillators and phase-locked oscillators used therein, the adaptive learning systems of the present invention include sample-and-hold (S&H) devices, and follow-and-hold devices. As known to those skilled in the art, both sample-and-hold devices and follow-and-
20 hold devices include an analog-to-digital (A/D) converter and a digital-to-analog (D/A) converter. Therefore, it is inherent that the present invention, as a subcombination, includes an A/D converter.

The frequency-hopping oscillators of the present invention include adaptive circuitry with learning and recalling functions, thereby providing
25 frequency-hopping oscillators in which an output frequency of a VCO can be channelized without waiting for phase locking.

The method of the present invention includes generating UP/DOWN signals by phase detecting, decoding the UP/DOWN signals into increment/decrement signals, recalling previously stored channelizing
30 information, parallel adding a single increment/decrement pulse to the recalled channelizing information in accordance with a sign (+1, 0, -1) of the

increment/decrement signal, and storing the corrected channelizing information in the RAM.

5 The method of the present invention further includes recalling the corrected channelizing information, repeating the parallel adding, storing, and recalling steps at a clock frequency to generate channelizing information that is progressively corrected, stored, and recalled, one increment/decrement pulse at a time, at the clock frequency.

10 The method of the present invention still further includes using the repeatedly recalled channelizing information, that is being corrected one increment/decrement pulse at a time at the clock frequency, to drive the output frequency progressively closer to phase lock substantially simultaneous with the parallel adding, storing, and recalling steps.

15 Therefore, the method of the present invention eliminates storing or latching steps, and therefore eliminates both the complexity in apparatus and the time that is required to perform housekeeping steps.

20 As shown and described herein, channelizing information, and/or frequency-correction information, is developed and stored that, when recalled will drive the output frequency to the desired channel almost instantly, and with very little deviation from frequencies that would phase lock for the respective channels.

25 The channelizing information compensates for errors in proportionality and linearity of such components as a D/A converter, an analog combiner/offsetter, resistor values, and/or a VCO. Subsequent return to the same channelized frequency results in automatic correction for temperature drift of various components that may have occurred since the channel was last accessed.

30 The frequency-hopping oscillators of the present invention include a digital integrator and special circuitry that mimics analog circuitry. That is, they each include circuitry that provides digital lead compensation, thereby providing loop stability for the digital integrators, even as analog integrators use a lead resistor in series with an integrating capacitor to achieve lead compensation and loop stability.

In first and second embodiments, lead compensation is achieved by analog summation of a channelizing voltage and a lead-compensating voltage. In a third embodiment, lead compensation is achieved by digital summation of digitized channelizing information and a digital lead-compensation signal.

5 In a fourth embodiment of an adaptive learning system, an output voltage is produced that is equal to an input voltage. If the input voltage varies as a function of time, the learning device is a digital sample-and-hold device; whereas, if the input voltage has a constant magnitude, or if the input voltage is sampled, the learning device is a sample-and-hold device.

10 As will be discussed in more detail subsequently, the learning systems of the present invention include not only frequency-hopping oscillators, but also sample-and-hold devices and follow-and-hold devices, and preferably, all of these adaptive learning systems include nonlinear D/A converters.

15 Since both digital sample-and-hold and follow-and-hold devices include an A/D converter, and the A/D converter includes a D/A converter, the present invention includes not only nonlinear D/A converters, but also nonlinear A/D converters.

20 Returning now to the nonlinear D/A converters of the present invention, whereas the primary design objective of prior-art D/A converters has been to produce output voltages that increase linearly in response to increases in binary-coded inputs, the improved D/A converters of the present invention produce analog outputs can be characterized as being intentionally nonlinear.

25 Whereas prior-art D/A converters provide analog outputs in which each higher bit hopefully produces a voltage that is exactly twice as high as the next lower bit, the D/A converters of the present invention can be characterized as producing analog outputs of a plurality of higher bits that are less than twice the analog output of each of a plurality of respective lower bits, irrespective of component variables.

30 The improved D/A converters of the present invention also can be characterized as producing analog outputs by a plurality of higher bits that are less than the sum of the outputs of all respective lower bits, irrespective of component variables.

The improved D/A converters of the present invention also can be characterized as producing analog outputs in response to a plurality of predetermined numerical inputs that are higher than the analog outputs produced by respective ones of next higher numerical inputs, irrespective of component variables.

The improved D/A converters of the present invention can be characterized as producing analog outputs with a plurality of downward steps, one for each increase in numerical input for a plurality of higher bits. That is, in a D/A converter of the present invention, if four bits are designed to produce downward steps, each of their fifteen numerical inputs would produce downward steps, irrespective of component variables.

Further, the improved D/A converters of the present invention can be characterized as having a plurality of dual addresses, irrespective of component variables. A D/A converter has dual addresses if the same analog output can be produced in response to two different digital inputs.

Still further, the improved D/A converters of the present invention can be characterized as being without holes, irrespective of component variables. By definition, a D/A converter has a hole if an increase by one in a digital input produces an increase in a voltage output that is at least twice as high as a normal increase in the output voltage.

If a D/A converter has a hole in its output voltage, one digital input may produce an analog output that is too low to satisfy a need, such as phase locking, and the next higher digital input may produce an analog output that is too high to satisfy a need, such as phase locking.

For instance, if an increase in a numerical input of 1 produced a voltage step significantly higher than an average, or nominal, voltage step, the hole would reduce the effective resolution of the D/A converter.

Holes are caused by accumulative errors in resistances in D/A converters. While 12-bit D/A converters are practical and relatively economical, it is difficult and expensive to prevent holes in D/A converters with a larger number of bits because of the larger number of resistor tolerances and the random accumulation of the resistor tolerances.

That is, in prior-art linear D/A converters, by random selection of resistors, resistor tolerances cause both holes, dual addresses, and resultant nonlinearities to occur erratically with respect to one or more bits, and every effort has been made to eliminate these characteristics.

5 In contrast, in the present invention, holes are absolutely abolished in any of the bits that are designed to function according to the present invention, dual addresses with respect to a plurality of higher bits are included in at least a plurality of higher bits, and the dual addresses are designed sufficiently large that variations in resistances of the various components can never eliminate any
10 of the dual addresses nor interject a hole in the place of any dual address.

The nonlinear D/A converters of the present invention allow lower cost resistors to be used, and allow a larger number of bits to be processed, even when low cost resistors are used.

Therefore, the present invention includes a nonlinear D/A converter
15 that excels over prior-art D/A converters in both performance and cost when used in phase-locked oscillators, and in learning systems such as adaptive frequency-hopping oscillators.

In summary, in frequency-hopping oscillators of the present invention channelizing information and/or frequency-correction information is generated
20 as increment/decrement pulses, the recalled channelizing information is corrected as an algebraic function of the increment/decrement pulses and at a clock frequency, the corrected channelizing information is used to drive the output frequency progressively closer to phase lock, and the recalling, correcting, driving, and storing steps are repeatedly repeated at the clock
25 frequency before changing to another channel.

When phase lock is achieved, the generating of increment/decrement pulses ceases except as required to correct for drift, the accumulative summed values in the RAM become channelizing information, which, when recalled, will drive the output frequency to approximate phase lock for a selected
30 channel in less than a microsecond.

In a first aspect of the present invention, a learning system having a learning path with a D/A converter that produces an output voltage as a function of a binary input, the improvement in which: the D/A converter

comprises a nonlinear D/A converter that produces a plurality of downward steps in the output voltage; and the downward steps are sufficiently large that manufacturing tolerances cannot obliterate any of them.

In a second aspect of the present invention, a method for producing
5 channelized output frequencies comprises: recalling previously stored channelizing information for one of the channels; repeatedly correcting the recalled channelizing information before recalling previously stored channelizing information for an other channelized frequency; and interposing storing and driving steps intermediate of the repeatedly correcting steps.

10 In a third aspect of the present invention, a method for producing channelized output frequencies comprises recalling previously stored channelizing information for one of the channels, driving an output frequency toward phase lock for the one channel, and comparing a feedback frequency with a reference frequency for the channelized output frequency, the
15 improvement which comprises: correcting the recalled channelizing information in response to the comparing step; storing the corrected channelizing information subsequent to the correcting step; driving the output frequency closer to phase lock in response to the correcting step; and repeating the correcting, driving, and storing steps before changing to an other of the
20 channelized frequencies.

In a fourth aspect of the present invention, a method for phase locking an output frequency comprises D/A converting binary-coded information into an output voltage, the improvement in which the D/A converting step
25 comprises: producing a plurality of downward steps in the output voltage; and preventing manufacturing tolerances from obliterating any of the downward steps.

In a fifth aspect of the present invention, a method for converting binary-coded inputs into an output voltage that varies as a function of the binary-coded information comprises: producing a plurality of downward steps
30 in the output voltage; and preventing manufacturing tolerances from obliterating any of the downward steps.

In a sixth aspect of the present invention, a method comprises clocking, counting, D/A converting, and comparing, the improvement which comprises:

producing a plurality of downward steps in an output voltage produced by the D/A converting; and preventing manufacturing tolerances from obliterating any of the downward steps.

5 In a seventh aspect of the present invention, a method for sampling and digitally holding an analog voltage comprises resetting, clocking, binary counting, D/A converting, and comparing, and the improvement which comprises: producing a plurality of downward steps in an output voltage produced by the D/A converting; and preventing manufacturing tolerances from obliterating any of the downward steps.

10 In an eighth aspect of the present invention, a method for following and digitally holding an analog voltage comprises analog following, analog holding, clocking, UP/DOWN counting, D/A converting, and comparing, the improvement which comprises: producing a plurality of downward steps in an output voltage produced by the D/A converting; preventing manufacturing
15 tolerances from obliterating any of the downward steps; correcting for errors produced by the downward steps; and the correcting step comprises continuing the counting subsequent to the analog holding.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

20 FIGURE 1 is a schematic drawing of a prior-art phase-locked loop with an analog integrator;

FIGURE 2 is a schematic drawing of a prior-art analog integrator for the phase-locked loop, similar to that of FIGURE 1, but in more detail;

FIGURE 3 is a graph of an integrated signal, showing lead compensation added thereto;

25 FIGURE 4 is a schematic drawing of a preferred embodiment of the present invention in which an adaptive frequency-hopping oscillator utilizes digital integration, and digital lead compensation is added by analog summing;

FIGURE 5 is a schematic drawing showing details of a decoder that is used in conjunction with the parallel adder in the embodiment of FIGURE 4;

30 FIGURE 6 is a schematic drawing of an embodiment of the present invention in which an adaptive frequency-hopping oscillator utilizes digital

integration, digital lead compensation is added by analog summing, and a PROM is used to provide initial channelizing information;

FIGURE 7 is a schematic drawing of an embodiment of the present invention in which an adaptive frequency-hopping oscillator utilizes digital integration, and lead compensation is added by digital summation of integration and lead-compensation signals, rather than the analog summation of FIGURES 4 and 6;

FIGURE 8 is a modification of a prior-art patent, showing how ac and dc modulation may be added to the frequency-hopping oscillators of the present invention;

FIGURE 9 is a schematic drawing of a conventional D/A converter that uses a ladder of R and 2R resistors;

FIGURE 10 is a diagram showing examples of variations in output voltages as caused by variations in resistances of the D/A converter of FIGURE 9;

FIGURE 11A is a diagram, in stepped form, showing that holes in output voltages of the D/A converter of FIGURE 9 may be caused by variations in resistances of standard resistors;

FIGURE 11B is a diagram, similar to FIGURE 11A, but showing in stepped form that variations in resistances of standard resistors may result in duplicate digital addresses;

FIGURE 12A is a diagram, showing in smoothed curve form, that variations in output voltages of the D/A converter of FIGURE 9 may cause holes;

FIGURE 12B is a diagram, showing in smoothed curve form, that variations in resistances of standard resistors may result in duplicate input addresses;

FIGURE 13 is a schematic drawing of a preferred embodiment of a nonlinear D/A converter for use with channelized phase-locked oscillators and frequency-hopping oscillators of the present invention;

FIGURE 14 is a diagram showing that voltage output vs. input for the conventional D/A converter of FIGURE 9 is linear;

FIGURE 15 is a diagram showing that voltage output vs. input for the D/A converter of FIGURE 13 is nonlinear;

FIGURE 16 is a block diagram of an embodiment of the nonlinear D/A converter of the present invention in which output voltages of 12-bit and 4-bit D/A converters are proportionally summed to provide nonlinearity;

FIGURE 17 is a schematic diagram of an embodiment of the nonlinear D/A converter of the present invention in which voltage summing of 12-bit and 4-bit D/A converters provides nonlinearity;

FIGURE 18 is a graph of output voltage vs. input, showing both the voltage output of a conventional linear D/A converter;

FIGURE 19 is a graph of output voltage vs. input of the nonlinear D/A converter of FIGURES 17, 21, and 22;

FIGURE 19A is a graph of output voltage vs. input, reproducing a portion of the graph of FIGURE 19 in an enlarged scale for the purpose of more clearly showing the downward steps that provide dual addresses;

FIGURE 20 is a graph of output voltage vs. input of the nonlinear D/A converter of FIGURES 17, 21, and 22, showing that, rather than allowing the output voltage to fall below a linear output voltage, the nonlinear output voltage may be raised to approximate the output of a conventional D/A converter;

FIGURE 21 is a schematic diagram of an embodiment of the nonlinear D/A converter of the present invention in which current summing is used to achieve nonlinear output voltages;

FIGURE 22 is a schematic diagram of an other embodiment of the nonlinear D/A converter of the present invention in which current summing is used to achieve nonlinear output voltages, and optionally, inverters are used to eliminate negative logic;

FIGURE 23 is a schematic drawing of a sample-and-hold device that includes an A/D converter therein as a subcombination, and that uses a nonlinear D/A converter such as those shown in FIGURES 13, 16, 17, 21, and 22, and as discussed in conjunction with FIGURES 10, 11A, 11B, 12A, 12B, 13-19, 19A, and 20-22; and

FIGURE 24 is a schematic drawing of a follow-and-hold device that includes an A/D converter therein as a subcombination, and that uses a nonlinear D/A converter such as those taught herein.

DETAILED DESCRIPTION OF THE INVENTION

5 Referring now to FIGURES 1 and 2, before considering the preferred embodiment of the present invention, a brief review of phase-locked oscillators and integrators may be helpful. Also, it is appropriate to review integrators with lead compensation, since lead compensation is necessary to achieve stability in phase-locked loops.

10 A prior-art phase-locked oscillator 10 of FIGURE 1 includes a reference oscillator 12, a divider 14 for dividing the reference frequency of the reference oscillator 12 by a constant value of M , a phase comparator, or phase detector, 16, an analog integrator 18, a voltage-controlled oscillator (VCO), or radio-frequency oscillator, 20, an output frequency conductor 22, and a feedback conductor 24. A divider 26 may be included to reduce operating frequencies of the phase detector 16 by dividing by N , or to achieve channelization of frequencies produced by the VCO 20 by dividing by selected values of N .

15 The phase-locked oscillator 10 also includes both a forward path 28 and a feedback path 30. The forward path 28 extends from the phase detector 16 to the output frequency conductor 22, and the feedback path 30 extends from the output frequency conductor 22 to the phase detector 16. Thus, by definition, the phase detector 16 is in neither the path 28 nor the path 30.

20 The integrator 18, as shown in FIGURE 1, includes an operational amplifier 32, a coupling resistor 34, an integrating capacitor 36, and a lead-compensation resistor 38. However, in actual practice, an analog integrator 40 of FIGURE 2 is used that includes a reference-frequency spurious-suppressing capacitor.

25 That is, the integrator 40 includes an operational amplifier 42, the coupling resistor 34, the integrating capacitor 36, the lead-compensation resistor 38, and a reference-frequency spurious-suppressing capacitor 44.

30 The operational amplifier 42 of FIGURE 2 includes a positive input terminal 46 that is connected to ground, as shown, and a negative input

terminal, or inverting input terminal, 48. As shown, the coupling resistor 34 is connected to the negative input terminal 48.

Since the positive input terminal 46 is grounded, the operational amplifier 42 will hold the negative input terminal 48 at virtual ground.

5 Therefore, if a constant positive voltage is applied to an input node 50, a constant current will flow through the coupling resistor 34 that is a function of the constant voltage and the resistance of the resistor 34.

10 Because of the high input impedance of the operational amplifier 42, there will be negligible current into the negative input terminal, or inverting input terminal, 48. This means that virtually all of the current from the voltage applied to the input node 50 will flow into the capacitor 36 and through the resistor 38. Therefore, the current flow into the capacitor 36 and through the resistor 38 will be equal to the current flow through the resistor 34 until integration is complete.

15 With a positive voltage at the input node 50, current flow is in a direction from the input node 50, to the negative input terminal 48, through the capacitor 36, and through the resistor 38 to an output node 52. Thus, positive and negative sides of the capacitor 36 are as shown for a positive input voltage at the node 50, and the integrator 40 ramps a voltage negatively between the
20 capacitor 36 and the resistor 38.

Because of the aforementioned current flow through the resistor 38, and the voltage drop across the resistor 38, a voltage is produced at the node 52 that is more negative than the negatively ramped voltage that is produced by the capacitor 36. This additional negative voltage provides lead compensation.
25 Lead compensation is required for stability of phase-locked oscillators, such as the phase-locked oscillator 10 of FIGURE 1.

The fact that lead compensation is required for stability of phase-locked loops is attested to by P.V. Brennan in *Phase-Locked Loops, Principles and Practice*, McGraw-Hill, 1996 in section 3.2, pages 33-37. As taught in
30 CMOS/NMOS, Special Functions Data, Series A, 1984, pages 6-43, the equation for damping is: $\zeta = (\omega \times R \times C)/2$, where R is the resistance of the lead-compensation resistor 38, and C is the capacity of the integrating capacitor

36. As seen by this formula, when R goes to zero, damping goes to zero which means that the phase-locked oscillator 10 becomes unstable.

In the embodiments of FIGURES 4, 6, and 7, digital integrators are provided with lead compensators that mimic the lead-compensation resistor 38 of FIGURES 1 and 2. A graph of FIGURE 3 will be helpful in understanding the digital lead compensators of FIGURES 4, 6, and 7.

Referring now to FIGURE 3, an increasing integrator output 58 is accompanied by a lead-compensation signal 60, thereby providing a lead-compensated output 62 that is more positive than the increasing integrator output 58 by a constant and predetermined magnitude. In like manner, a decreasing integrator output 64 is accompanied by a lead-compensation signal 66, thereby providing a lead-compensated output 68 that is more negative than the decreasing integrator output 64 by a constant and predetermined magnitude.

As the integrator output 58 of FIGURE 3 increases, an output frequency in the output frequency conductor 22 of FIGURE 1 moves toward phase lock with the reference oscillator 12.

Referring now to FIGURE 4, before reciting the structure and operation in detail, a brief preview will be presented. This overview should not only be clearly understandable, but should also make the detailed description easier to understand.

An adaptive frequency-hopping oscillator, or adaptive system, or learning system, 72 includes a phase-locked oscillator 74. The phase-locked oscillator 74 includes the reference oscillator 12, the divider 14, a phase comparator, or phase detector, 76, the VCO 20, the output frequency conductor 22, and a divider 78 in which N is controllable digitally by a command signal in a command bus, or bundle of frequency-command conductors, 80.

Assuming that one channelized frequency has been selected for the first time by the frequency-command conductors 80, channelizing information for this one channelized frequency is digitally integrated from frequency-correction information produced by the phase detector 76, thereby generating channelizing information.

As will be described in detail subsequently: the method of the present invention includes developing UP/DOWN signals by phase comparing; converting the UP/DOWN signals into increment/decrement signals by decoding; recalling previously stored channelizing information; parallel adding one increment/ decrement pulse to the recalled channelizing information as an algebraic function of one of the increment/decrement signals; and storing the parallel-added sum.

The method of the present invention further includes: repeating the recalling, parallel adding, and storing steps at the frequency of the reference oscillator 12; and driving an output frequency of the VCO 20 toward phase lock with the reference oscillator 12 in response to recalling and D/A converting steps that are repeated at the frequency of the reference oscillator 12.

Although the channelizing information for this one channelized frequency is developed and stored in digital form during the learning process, it proceeds to the VCO 20 through D/A and analog components that produce errors. Therefore, when phase lock occurs, the channelizing information has been compensated for analog errors in proportionality and linearity.

Thereafter, when this one channelized frequency is selected and the respective channelizing information is recalled from a digital memory and D/A converted into a channelizing voltage, the VCO 20 will be driven to an output frequency that almost equals the output frequency at phase lock.

Further, each time that this same channelized frequency is selected, the channelizing information is updated for any error in output frequency such as temperature drift of analog or D/A components. Error signals are processed by the phase detector 76 at the frequency of the reference oscillator 12, so that this updating occurs even if the output frequency remains at one channelized frequency for a very short period of time.

Inclusion of the divider 14 allows increasing a frequency of the reference oscillator 12 in excess of an allowable frequency of operation of the phase detector 76, thereby providing an exceptionally fast sampling rate.

Continuing to refer to FIGURE 4, the frequency-hopping oscillator 72 utilizes a digital integrator 82 and a digital lead compensator, or lead signal

means, 84. The digital integrator 82 and the digital lead compensator 84 provide a lead-compensated digital integrator 86.

However, before discussing the digital integrator 82 and the digital lead compensator 84, it is important to consider the phase detector 76 in more detail. The phase detector 76, which preferably is Motorola part number 45152, has three output states. That is, an output in an UP conductor 88, and an output in a DOWN conductor 90 may separately be either a binary 1 or a binary 0, but since the phase detector 76 does not output 0,0, it outputs only three states.

When the UP conductor 88 produces a 0, and the DOWN conductor 90 produces a 1, these outputs reflect the fact that the frequency produced by the VCO 20 is too low. Conversely, when the UP conductor 88 produces a 1, and the DOWN conductor 90 produces a 0, these outputs reflect the fact that the frequency of the VCO 20 is too high. And when both of the conductors, 88 and 90, produce a 1, the frequency-hopping oscillator 72 is phase locked.

The digital integrator 82 includes a pulse decoder 92, a parallel adder 94, and a RAM 96. A D/A converter 98 and a low-pass filter 100 convert the digital signal to an analog voltage that is suitable for driving the VCO 20.

In operation, the decoder 92 receives one of the three output states (0,1; 1,0; or 1,1) from the phase detector 76, as noted above, and delivers separate and distinct single-bit outputs to the parallel adder 94. Either one of the two digital outputs will remain constant until the output condition of the phase detector 76 changes to another one of the three output states. A more detailed description of the decoder 92 and the parallel adder 94 will be provided in conjunction with FIGURE 5.

The parallel adder 94, which is a 16-bit device, utilizes the binary outputs of the decoder 92 as sixteen 0's, fifteen 0's followed by a 1, or sixteen 1's.

Digital integration is achieved as follows: the RAM 96, which is connected to the reference oscillator 12 by a sampling-rate conductor 102, accepts a first sample, or a first increment/decrement pulse, of the digital output provided by the decoder 92 via the parallel adder 94 and a 16-bit data-in bus 104. This increment/decrement pulse is stored in the RAM 96.

At the frequency of the reference oscillator 12, this first increment/decrement pulse is delivered back to the parallel adder 94 via a 16-bit data-out bus 106 to be algebraically summed with a second sample, or a second increment/decrement pulse, the algebraic sum of the first and second increment/decrement pulses are delivered to the RAM 96 via the data-in bus 104, and this algebraic sum is delivered back to the parallel adder 94 via the data-out bus 106. This cycle repeats at the frequency of the reference oscillator 12 until the frequency-hopping oscillator 72 is in phase lock, or until the frequency command in the command bus 80 is changed.

Simultaneously with the process of digital integration as described above, the progressively and algebraically summed values are delivered to the D/A converter 98 which is capable of processing sixteen bits of information, an analog voltage is outputted by the D/A converter 98 and delivered to the low-pass filter 100, and the filtered analog voltage is applied to the VCO 20 through a combiner/offsetter 108 until the frequency-hopping oscillator 72 phase locks.

This process of digital integration is repeated the first time a frequency command in the command bus 80 selects a channelized frequency by changing the value of N, thereby changing the output frequency at which the frequency-hopping oscillator 72 will phase lock. And, each time the frequency-hopping oscillator 72 phase locks to a selected frequency, the digitally integrated outputs are stored in the RAM 96.

The next time the frequency-hopping oscillator 72 hops to a channelized frequency, the frequency command changes the value of N, and the RAM 96 cooperates with the D/A converter 98 the low-pass filter 100, and the combiner/offsetter 108 to supply a channelizing voltage to the VCO 20, and thereby drive the VCO 20 to an output frequency that approximates phase lock for the selected channelized frequency. This channelizing occurs in less than one microsecond.

It can be seen that the digital values stored in the RAM 96 are the values that, for a given time and temperature, correct for production variations in proportionality, nonlinearities, and temperature drifts of the D/A converter 98, the combiner/offsetter 108, and the VCO 20.

That is, as the RAM 96 digitally integrates a channelizing voltage that will phase lock the system, the RAM-stored digital values are inherently compensated for analog inaccuracies of the D/A converter 98, the combiner/offsetter 108, and the VCO 20. Phase lock is accomplished by
5 applying RAM-accumulated values that keep correcting until phase lock is achieved.

It is important to notice that the channelizing information will be updated each time a given channelized frequency is produced, and the stored channelizing information will be updated at the frequency in the sampling-rate
10 conductor 102, unless that channelized frequency is already in phase lock, if the frequency-hopping oscillator 72 remains at that channelized frequency for a period of time that allows the phase detector 76 to provide even one signal in one of the conductors, 88 or 90.

For example, if the reference oscillator 12 is producing a reference
15 frequency of 8.0 Mhz, and the divider 14 is dividing by 128, the phase detector 76 will be operating with a reference frequency of 62,500 Hz.

In this example, in 125 nanoseconds after receiving either an UP or a DOWN signal from the phase detector 76, the RAM 96 will obtain a sample for algebraic addition to the value previously stored in the RAM 96 for that given
20 channelized frequency.

Continuing to refer to FIGURE 3, as previously mentioned, the lead-compensated digital integrator 86 includes the digital lead compensator 84. And, as also previously mentioned, the digital lead compensator 84 performs the function of the resistor 38 of FIGURES 1 and 2.

25 Since the output of a decoder 110 is always of the same sense as the output of the decoder 92, the output of the decoder 110 is a lead-compensating signal. All that remains is to apply this lead-compensating signal to the VCO 20 as a voltage.

That is, an increasing integrator output 58 as shown in FIGURE 3, of
30 the digital integrator 82 of FIGURE 4, is accompanied by a lead-compensation signal 60, so that a lead-compensated output 62 of FIGURE 3 is the sum of both the output of the digital integrator 82 and the digital lead compensator 84.

In the preferred embodiment of FIGURE 4, application of the lead-compensating signal to the VCO 20 is via a 2-bit D/A converter 112, a low-pass filter 114, and the combiner/offsetter 108.

5 The combiner/offsetter 108 algebraically adds the lead-compensating signal, as converted to an analog voltage by the D/A converter 112 and filtered by the low-pass filter 114, to the output of the digital integrator 82, as stored in the RAM 96, and as converted to an analog voltage by the D/A converter 98 and filtered by the low-pass filter 100.

10 As described above, it can be seen that the digital lead compensator 84 includes the decoder 110, the D/A converter 112, and the combiner/offsetter 108, although only the combiner portion is actually a part of the digital lead compensator 84.

The combiner/offsetter 108 serves two functions, as named. It functions as an algebraic summer of analog voltages, and it offsets the summed and amplified signal to a voltage that is in the linear tuning range of the VCO 20.

15 The frequency-hopping oscillator 72 includes a phase-locked loop 116. The phase-locked loop 116 includes both a forward path 118 and a feedback path 120. The forward path 118 extends from the phase detector 76 to the output frequency conductor 22 via the digital integrator 82, the combiner/offsetter 108, and the VCO 20. The feedback path 120 extends from the output frequency conductor 22 to the phase detector 76 via a feedback conductor 122 and the divider 78 and includes both the divider 78 and the feedback conductor 122.

25 If a backup battery 124 is included at the factory, the frequency-hopping oscillator 72 will learn to compensate for variations in component proportionalities and nonlinearities during burn-in. If the battery 124 is not included, the frequency-hopping oscillator 72 will learn to compensate for variations in component proportionalities and nonlinearities each time the frequency-hopping oscillator 72 is initiated.

30 In operation, a frequency is selected by a source separate from, and not a part of, the present invention. The command for this frequency is delivered to the RAM 96 via the command bus 80 through which a digitized address representing this selected frequency is transmitted.

As will be described in conjunction with the embodiment of FIGURE 6, the decoder 110 and the D/A converter 112 can be replaced by a device that includes only three components: an inverter and two resistors.

For a more complete understanding of the embodiment of FIGURE 4, and also of FIGURES 6 and 7, the decoder 92 is shown in FIGURE 5 and is described in detail therewith. To more clearly show and describe connections of the decoder 92 of FIGURE 5 with FIGURES 4, 6, and 7, conductors 126 and 128 are shown in FIGURES 4-7. The parallel adder 94 is also shown in more detail in FIGURE 5. More particularly, the conductor 126 of FIGURES 4 and 5 is shown connected to bits A1 to A15, and the conductor 128 is shown connected to a bit A0.

Referring now to FIGURE 5, In operation, 1 is added by the parallel adder 94 when a 1 is supplied to the A0 bit via the conductor 128 and 0's are applied to the bits A1 to A15 via the conductor 126. Since binary subtraction by 1 is accomplished by adding 1 to all bits, 1 is subtracted from the parallel adder when a 1 exists in both conductors, 126 and 128.

Further, since the sampling-rate conductor 102 connects the reference oscillator 12 to the parallel adder 94, the parallel adder 94 continues to add 1 or to subtract 1 at the frequency of the reference oscillator 12.

Continuing to refer to FIGURE 5, the decoder 92 includes an AND gate 130, and inverter 132, and a NAND gate 134.

In operation, when an output frequency of the VCO 20 of FIGURE 4 is too low, the UP conductor 88 outputs a 0, and the DOWN conductor 90 outputs a 1. The inverter 132 of FIGURE 5 inverts its 1 input to a 0, so that both inputs to the AND gate 130 are 0, and the AND gate 130 outputs a 0 to the bits A1-A15 via the conductor 126, since AND gates output a 1 only when both inputs are 1.

At this time, the UP conductor 88 delivers a 0 to the NAND gate 134 and the DOWN conductor 90 delivers a 1 to the NAND gate 134, so that the NAND gate 134 delivers a 1 to the A0 bit via the conductor 128, since NAND gates output a 0 only when both inputs are 1.

With 0's applied to bits A1-A15, and with a 1 applied to bit A0, the parallel adder 94 continues to add ones as long as the UP conductor 88 produces a 0 and the DOWN conductor 90 produces a 1.

5 When an output frequency of the VCO 20 is too high, the UP conductor 88 produces a 1, the DOWN conductor 90 produces a 0, the NAND gate 134 delivers a 1 to the bit A0, the AND gate 130 delivers a 1 to the bits A0-A15, and the parallel adder 94 subtracts at a rate determined by the reference oscillator 12.

10 When the phase-locked oscillator 74 of FIGURE 4 is in phase lock, the UP conductor 88 produces a 1, the DOWN conductor 90 produces a 1, the NAND gate 134 delivers a 0 to the bit A0, the inverter 132 and the AND gate 130 cooperate to deliver a 0 to the bits A0-A15, and the parallel adder 94 neither adds nor subtracts.

15 Referring now to FIGURE 6, an adaptive frequency-hopping oscillator, or adaptive system, or learning system, 136 includes components as identified in conjunction with the adaptive frequency-hopping oscillator 72 of FIGURE 4, except as included in the following description. One of the differences between the embodiments of FIGURES 4 and 6 resides in apparatus that FIGURE 6 uses to achieve lead compensation. This will be described before
20 discussing the adaptive system 136 as a whole.

The adaptive frequency-hopping oscillator 136 of FIGURE 6 includes an analog decoder 138 that replaces both the decoder 110 and the D/A converter 112 of the adaptive frequency-hopping oscillator 72 of FIGURE 4. While the decoder 110 and the D/A converter 112 illustrate the necessary
25 functions, the decoder 138 is the actual device that would be used in the embodiments of FIGURES 4 and 6.

The decoder 138 includes an inverter 140 and resistors 142A and 142B. The resistors 142A and 142B have equal resistances.

30 When phase lock occurs, the phase comparator 76 delivers UP and DOWN signals of 5.0 volts. Since the 5.0 volt UP signal is inverted by the inverter 140, 0.0 volts is applied to the resistor 142A, 5.0 volts is applied to the resistor 142B, and 2.5 volts are delivered to a conductor 144. Therefore, 2.5 volts is the lead-compensating null voltage.

When an output frequency from the VCO 20 is too low to phase lock, the phase comparator 76 delivers an UP signal of 0.0 volts and a DOWN signal of 5.0 volts. Since the 0.0 volt UP signal is inverted by the inverter 140, 5.0 volts are applied to both resistors, 142A and 142B, 5.0 volts is delivered to the conductor 144 that is connected between the resistors, 142A and 142B, and a lead-compensation voltage of 5.0 volts, which is 2.5 volts greater than null, is delivered to the VCO 20 via the combiner/offsetter 108. The lead-compensation voltage delivered to the VCO 20 may be 5.0 volts, or as proportioned in the combiner/offsetter 108.

When an output frequency from the VCO 20 is too high to phase lock, the phase comparator 76 delivers an UP signal of 5.0 volts and a DOWN signal of 0.0 volts. Since the 5.0 volt UP signal is inverted by the inverter 140, 0.0 volts are applied to both resistors, 142A and 142B, 0.0 volts is delivered to a conductor 144 that is connected between the resistors, 142A and 142B, and a lead-compensation voltage of 0.0 volts, which is 2.5 volts lower than null, is applied to the VCO 20.

Since the same UP and DOWN signals are delivered to the decoder 92, which is a part of a digital integrator 146, when the digital integrator 146 is counting upwardly and the D/A converter 98 is producing an ever-increasing voltage, the decoder 138 produces its highest lead-compensating voltage.

In like manner, when the digital integrator 146 is counting downwardly, the decoder 138 supplies 0.0 volts to the combiner/offsetter 108. Since 0.0 volts is lower by 2.5 volts than the lead-compensating null voltage of 2.5 volts, the combiner/offsetter 108 reduces the voltage applied to the VCO 20 by the D/A converter 98. Thus as described here, and as shown in FIGURE 3, lead compensation is always in the same direction as integration.

The decoder 138 cooperates with the combiner/offsetter 108 to provide a digital lead compensator 148, and the digital lead compensator 148 cooperates with the digital integrator 146 to provide a lead-compensated digital integrator 150. The lead-compensated digital integrator 150 is part of a phase-locked oscillator 152, and the phase-locked oscillator 152 is a part of the adaptive frequency-hopping oscillator 136. The phase-locked oscillator 152 includes a forward path 154 and the feedback path 120. Identification of

components included in the paths, 154 and 120, can be made by comparing the embodiments of FIGURES 4 and 6.

A PROM 158 is preloaded with channelizing information such that when this channelizing information is converted to an analog channelizing voltage via the D/A converter 98, the output frequency of the frequency-hopping oscillator 136 will be near phase lock.

The channelizing information that is preloaded into the PROM 158 may be values that will produce output frequencies having nominal, or handbook, performance characteristics, but that will produce output frequencies that vary in accordance with actual variations in proportionality and linearity of the D/A converter 98, the combiner/offsetter 108, and the VCO 20. Even though the values of the channelizing information that are burned into the PROM 158 are only average values, several seconds are saved in achieving phase lock at start-up.

If the PROM 158 is of the electrically erasable type, the PROM 158 may be manually programmed, starting from an average value, to produce a zero output from a RAM 160, thereby programming the PROM 158 in accordance with actual system performance. Or, if the RAM 160 includes sixteen bits or more, the frequency-hopping oscillator 136 may be run through all channelized frequencies, and then the phase-locking values of the channelizing information that developed in the RAM 160 may be duplicated in the PROM 158, thereby extending the adaptive characteristics of the frequency-hopping oscillator 136 to the PROM 158.

Starting with the PROM 158 loaded by any suitable method, such as any of the three described above, if, upon start-up, the VCO 20 is operating at too low an output frequency, for a given channel, to phase lock with the reference oscillator 12, the decoder 92 commands a parallel adder 162 to place digitized frequency-correcting information into the RAM 160. Then the contents of the RAM 160 are added to the digital output of the PROM 158 by a parallel adder 162. The result is an analog channelizing voltage, as produced by the D/A converter 98, driving the VCO 20 to phase lock.

Preferably, the PROM 158 is, at least, a 16-bit device. However, unless the RAM 160 is used to determine the channelizing information that is

to be burned into the PROM 158, the RAM 160 may be an 8-bit device. Or, it may include even fewer bits, since it will need to store only frequency-correction information that supplements that of the PROM 158.

5 While the use of the PROM 158 has been shown and described in conjunction with FIGURE 6, which is a variation of the FIGURE 4 embodiment, it will be apparent that the same principles may be applied to other embodiments of frequency-hopping oscillators, such as those of FIGURES 4 and 7.

10 Referring now to FIGURE 7, an adaptive frequency-hopping oscillator, or adaptive system, or learning system, 170 includes parts that are like-named and like-numbered with those shown and described in conjunction with FIGURE 4. In addition, the adaptive frequency-hopping oscillator 170 includes a phase-locked oscillator 172.

15 The phase-locked oscillator 172 includes a phase-locked loop 174 with a forward path 176 and the feedback path 120. An amplifier/offsetter 178 is in the forward path 176, as are parts that are like-numbered and like-named with those shown and described in conjunction with FIGURE 4.

20 The phase-locked oscillator 172 also includes the digital integrator 146 of FIGURE 4 and a digital lead compensator 180. The digital integrator 146 and the digital lead compensator 180 cooperate to provide a lead-compensated digital integrator 182.

The digital integrator 146 includes the pulse decoder 92, the parallel adder 94, and the RAM 96. The digital lead compensator 180 includes the pulse decoder 92 and a parallel adder 184.

25 Operation of the lead-compensated digital integrator 182 is as follows: the phase detector 76 produces UP and DOWN signals, the pulse decoder 92 produces +1, -1, and 0 signals in accordance with UP signals, DOWN signals, and/or the absence of either an UP or a DOWN signal. The parallel adder 94 sums signals received from the pulse decoder 92, and the digital sums are
30 stored in the RAM 96. These digitally stored sums, or digitally stored numbers are channelizing information which, when D/A converted, become channelizing voltages.

When a digitally stored sum is recalled from the RAM 96, it is directed to the D/A converter 98 via the parallel adder 184 wherein lead compensation is added. In accordance with a digital number provided by the pulse decoder 92, the parallel adder 184 adds to, subtracts from, or leaves the same, the
5 digitally stored number received from the RAM 96, thereby adding lead compensation to channelizing information stored by, and recovered from, the RAM 96. Therefore, the voltage produced by the D/A converter 98 is a lead-compensated channelizing voltage.

Referring now to FIGURES 4, 6, and 7, significant differences in these
10 embodiments reside in the digital lead compensators, 84, 148, and 180. The frequency-hopping oscillators, 72 of FIGURE 4 and 136 of FIGURE 6, add lead compensation by analog summation in the combiner/offsetter 108, of a channelizing voltage and a lead-compensation voltage. In contrast, the frequency-hopping oscillator 170 of FIGURE 7 adds lead compensation by
15 digital summation of digitized channelizing information and a digital lead-compensation signal in the parallel adder 184.

Referring now to FIGURE 8, an adaptive frequency-hopping oscillator, or adaptive system, or learning system, 190 illustrates how the frequency-hopping oscillators and the lead-compensated digital integrators of the present
20 invention can be combined with any of the dc modulated phase-locked oscillators of the aforesaid Lautzenhiser patents.

The frequency-hopping oscillator 190 incorporates components of FIGURE 6 of Lautzenhiser, U.S. Patent 5,091,706, which includes a detailed description of FIGURE 6, said Lautzenhiser patent being incorporated herein by
25 reference thereto.

Referring again to FIGURE 8, the frequency-hopping oscillator 190 may be ac and/or dc modulated. That is, both a forward path 192 and a feedback path 194 of a phase-locked oscillator 196 may be modulated by various means as taught in the aforesaid Lautzenhiser patents.

30 The frequency-hopping oscillator 190 of FIGURE 8 includes a block 198 that represents components shown and described in conjunction with the frequency-hopping oscillator 72 of FIGURE 4, as named and numbered in the block 198. That is, the block 198 represents inclusion of the lead-compensated

digital integrator 86, the parallel adder 94, the RAM 96, the D/A converter 98, and the combiner/offsetter 108 in the forward path 192 of the frequency-hopping oscillator 190 of FIGURE 8.

Attachment of the frequency-command conductors 80 to the RAM 96 of FIGURE 4 is represented in FIGURE 8 by connection of the frequency-command conductors 80 to the block 198; and connection of the frequency-command conductors 80 to the divider 78 of FIGURE 4 is represented by connection of the frequency-command conductors 80 to a block 200 that contains components as named therein. Therefore, the forward path 192 is channelized as taught in conjunction with FIGURE 4, and channelization of the feedback path 194 is achieved by the divider 78, as controlled by the frequency-command conductors, as taught in conjunction with FIGURE 4.

Modulation of the feedback path 194 is accomplished by a modulation oscillator 202, a bistable multivibrator 204, another bistable multivibrator 206, an OR gate 208, and a dual-modulus divider 210, in response to a modulation voltage being supplied to the modulation oscillator 202 via a modulation conductor 212, as taught in conjunction with FIGURE 6 in the aforesaid Lautzenhiser patent. The dual-modulus divider 210 is interposed into a feedback conductor 214.

Modulation of the forward path 192 is accomplished by interposing a summing resistor 216 into a forward path conductor 218, and supplying the modulation voltage of the modulation conductor 212 to the forward path conductor 218 is via a modulation resistor 220.

Returning now to the discussion of the embodiments of FIGURES 4, 6, and 7, channelizing information is any information that will drive an output frequency approximately to a channelized frequency. Frequency-correcting information is used to progressively correct channelizing information, so that the corrected channelizing information will drive an output frequency approximately to phase lock.

Generation of frequency-correcting information and channelizing information is via a learning path 222 of FIGURE 4, a learning path 224 of FIGURE 6, a learning path 226 of FIGURE 7, and a learning path 228 of FIGURE 8. Each learning path, 222, 224, 226, or 228 includes components of

a system that function together to provide frequency-correction information, thereby providing an adaptive system that compensates for lack in precision in proportionality and/or linearity and temperature drift in components that include analog inputs or outputs.

5 The learning path 222 of FIGURE 4 includes the phase detector 76, the decoder 92, the parallel adder 94, the RAM 96, the D/A converter 98, the low-pass filter 100, the combiner/offsetter 108, the VCO 20, and the feedback path 120.

10 The learning path 224 of FIGURE 6 includes the phase detector 76, the decoder 92, the parallel adder 162, the RAM 160, the parallel adder 164, the D/A converter 98, the low-pass filter 100, the combiner/offsetter 108, the VCO 20, and the feedback path 120.

15 The learning path 226 of FIGURE 7 includes the phase detector 76, the decoder 92, the parallel adder 94, the RAM 96, the parallel adder 184, the D/A converter 98, the low-pass filter 100, the combiner/offsetter 108, the VCO 20, and the feedback path 120.

 The learning path 228 of FIGURE 8 includes the phase detector 76, the parallel adder 94, the RAM 96, the D/A converter 98, the combiner/offsetter 108, and the VCO 20.

20 Referring now to FIGURE 9, a prior-art D/A converter 240 includes bits, or binary inputs, 242 for sixteen bits of binary-coded information, and an output voltage node 244. The D/A converter 240 includes a plurality of resistors R and a plurality of resistors 2R. Each of the resistors R have equal resistances. In like manner, all of the resistors 2R have equal resistances, but
25 their resistances are twice the values of the resistances of the resistors R.

 Any combination of the binary inputs 242 may be connected selectively to 10.0 volts, or any other suitable voltage to represent a binary input 242 of 1, or connected to ground to represent a binary input 242 of 0. The resultant voltage output at the node 244 will be a function of the binary
30 inputs 242, as determined by connecting selective ones of the binary inputs 242 to 10.0 volts or ground.

 For example, with 10.0 volts applied to sixteen binary inputs 242, that is with sixteen binary inputs 242 equal to a binary 1, the numerical input will

be 65,535 which is one less than 2 to the 16th power, and the theoretical voltage output will be $(10 \times 65,535)/65,536 = 9.999847$.

Referring now to FIGURE 10, a voltage curve 250 illustrates some of the variations in output voltage vs. numerical input that commonly occur with the prior-art D/A converter 240 of FIGURE 9.

While, in the discussion that follows, problems caused by error in resistances of the resistors 2R will be discussed, it should be apparent that the errors in the resistors R will also be involved, since each pair of R and 2R resistors outputs a voltage to the next higher bit.

For an input of 16,383, the first fourteen bits, or binary inputs, 242 are at 1. But for an input of 16,384, a fifteenth binary input 242 of FIGURE 9 is at 1 and the fourteen binary inputs 242 that were at 1 are now at 0. Therefore, errors in resistances in the fourteen resistors 2R of FIGURE 9 that had inputted 16,383 and whose errors in resistances may be accumulative either negatively or positively, are now connected to ground rather than to 10.0 volts, and a resistor 2R at the fifteenth bit 242 that represents 16,384 is connected to 10.0 volts.

Referring now to FIGURES 9 and 10, the change from the accumulative error of the fourteen resistors 2R of FIGURE 9 that were connected to 10.0 volts to an error in a single, or fifteenth, resistor 2R being connected to the 10.0 volts may result in the voltage curve 250 of FIGURE 10 stepping vertically up to a curve 252, or stepping vertically down to a curve 254 in response to a change from 16,383 to 16,384 in an input.

As a second example, for an input of 32,767, fifteen inputs 242 of FIGURE 9 are at binary 1's. But for an input of 32,768, a sixteenth input 242 is a binary 1 and the fifteen inputs 242 that were at binary 1's are now 0's. Therefore, errors in resistances in fifteen of the resistors 2R of FIGURE 9, that may be accumulative either negatively or positively, are now replaced by a single resistor 2R at the sixteenth bit 242.

This change from the accumulative error of the fifteen resistors 2R to an error in the single, or sixteenth, resistor 2R may result in the voltage curve 250 of FIGURE 10 stepping vertically up to a curve 256, or stepping vertically down

to a curve 258 in response to a change from 32,767 to 32,768 in a numerical input.

Referring now to FIGURES 11A and 11B, these figures are included to teach the same truths as FIGURE 10, but illustrate them differently.

5 Rather than the voltage output of the prior-art D/A converter 240 being in the form of a smooth curve, as illustrated in FIGURE 10, in actuality, a stepped output voltage curve 260 of FIGURE 11A steps upwardly in theoretically equal voltage steps 262 with each increase in a numerical input.

10 As illustrated by the stepped output voltage curve 260 of FIGURE 11A, an unduly large upward step 264 in output voltage may occur when an input of 32,767 is increased to 32,768 and errors in fifteen resistors 2R are replaced by an error in a different resistor 2R of FIGURE 9 at the sixteenth bit 242.

15 Therefore, in the illustration of FIGURE 11A there is a hole between these two digital inputs in that the D/A converter 240 of FIGURE 9 cannot produce a voltage step 265, which is shown by a phantom line, between inputs of 32,767 and 32,768. That is, a hole exists because the output voltage 260 increases, in response to a digital increase of 1, that is at least twice as large as the step 265.

20 Or, as illustrated in FIGURE 11B, a downward step 266 in a stepped output voltage curve 268 may occur when an input is changed from 32,767 to 32,768 and errors in fifteen resistors 2R are replaced by an error in a different resistor 2R at the sixteenth bit 242. Downward steps 266 produce dual addresses which will be discussed in conjunction with FIGURE 12B.

25 The output voltages of D/A converters, which actually are stepped, as shown in FIGURES 11A and 11B, may also be represented as smoothed curves, as in FIGURES 12A and 12B.

30 Referring now to FIGURE 12A, an output voltage curve 270 of the prior-art D/A converter 240 of FIGURE 9 shows how one or more holes may occur because of accumulative errors of the resistors 2R in lower bits, and replacement by a single resistor 2R in the next higher bit. In FIGURE 12A the output voltage jumps from an output voltage 272 to an output voltage 274 with an upward step 275 in response to a change in an input from 32,767 to 32,768, thereby leaving a hole, as discussed in conjunction with FIGURE 11A.

Referring now to FIGURE 12B, an output voltage curve 276 of the prior-art D/A converter 240 of FIGURE 9 shows that accumulative errors in the resistors 2R may result in a decrease in an output voltage 278 to an output voltage 280 with an increase in an input from 32,767 to 32,768.

5 Therefore, accumulative errors in the resistors 2R, instead of producing an upward step in the output voltage, may produce a downward step 281. Thus, instead of producing holes, a D/A converter may include downward steps 281 that produce duplicate digital addresses, or dual digital addresses. A dual digital address refers to a phenomena in which a desired output voltage can be
10 obtained by either of two different digital addresses.

As an example, in the output voltage curve 276, an output of 5.0 volts can be obtained by inputting a digital input of 32,668, or it can be obtained by inputting an input of 32,868. Thus, 32,668 and 32,868 are duplicate digital
15 addresses, or dual digital addresses, in that they produce the same output voltage. In like manner, various voltages can be outputted in response to either of two inputs, as can be seen by inspection of FIGURE 12B.

Referring now to FIGURE 13, a nonlinear D/A converter 282 of the present invention includes a plurality of the resistors R, three of which are labeled R16, R15, and R14 to identify them with their respective bits, and a
20 plurality of the resistors 2R, three of which are labeled 2R16, 2R15, and 2R14 to identify them with their respective bits.

The resistors R are arranged as shown, with resistances of resistors 2R nominally being twice as large as resistances of resistors R, as described in conjunction with FIGURE 9, a plurality of the binary inputs 242, and the output
25 voltage node 244. However, in addition to resistors R and 2R, the nonlinear D/A converter 282 includes a plurality of resistors ΔR , three of which are labeled $\Delta R16$, $\Delta R15$, and $\Delta R14$ to identify them with their respective bits.

For the sake of simplicity, for the discussion that follows, reference to resistors will be made without individual bit designation. That is, R, 2R, and
30 ΔR will be used to refer to resistors for all bits.

This series arrangement of resistors 2R with ΔR illustrates the use, in an actual design, of resistors 2R with resistances, whether fixed or variable, that are greater than twice the resistance of the resistors R.

The effect of increasing the resistances of the resistors $2R$, is to insert dual addresses, as shown in FIGURE 12B, at each bit 242 wherein the resistances of the respective resistors $2R$ have been increased, thereby eliminating any possibility of holes.

5 As can be appreciated, as the number of bits 242 increase in response to increasing binary inputs 242, and the number of resistors $2R$ that are used to convert a number increases, accumulative errors in the resistors $2R$ can cause holes that more seriously effect D/A conversion.

10 Therefore, while it may not be necessary to use the resistors ΔR for all bits, a sufficient number must be included to prevent holes, or to avoid the expense of providing, or matching, the resistors precisely enough to prevent holes.

15 Ideally, each higher bit will produce a slightly smaller voltage than the sum of all smaller bits. Thus, it can be seen that resistances of each of the resistors ΔR will not necessarily be equal. And, since the resistances of the ΔR resistors merely symbolize increasing resistances of the resistors $2R$, it becomes apparent that resistances of the resistors $2R$ may not be equal.

20 Optionally, rather than increasing resistances of the resistors $2R$, decreasing resistances of some, or all, of the resistors R will also produce a nonlinear D/A converter as taught herein. And, it becomes apparent that the resistances of all of the resistors R may not necessarily be equal. Instead, in accordance with individualized design criteria, resistances of all of the resistors, R and $2R$, may be selected by a computer analysis.

25 Referring now to FIGURE 14, the objective of prior-art D/A converters has been to convert inputs, in binary form, to output voltages that increase linearly with an increase in the digital input, as illustrated by an output voltage curve 284. However, as shown and described above, it has been difficult to produce D/A converters that do not have holes, as illustrated in FIGURES 11A and 12A, as the number of bits has increased beyond twelve.

30 In contrast to prior-art D/A converters in which output linearity has been the design criteria, the present invention provides a nonlinear D/A converter in which holes are eliminated and dual addresses are provided for one or more of the higher bits irrespective of resistor tolerances, manufacturing

cost is minimized, and the number of bits can be increased beyond normal limitations without incurring holes or requiring ultra-precision resistors.

Referring now to FIGURE 15, instead of producing an output 284 of FIGURE 14 that is a straight line, as is the design goal of the prior-art D/A converter 240 of FIGURE 9, the D/A converter 282 of FIGURE 13 produces an
5 output voltage curve 286 that slopes downwardly as digital inputs increase.

Further, in prior-art D/A converters, the voltage steps 262 of FIGURE 11A are designed to be equal. Thus, each higher bit produces twice the output voltage of the next lower bit. In contrast, in the present invention, for bits 242
10 of FIGURE 13 wherein ΔR resistors are included, each higher bit produces an output voltage that is less than twice that of the next lower bit, irrespective of resistor tolerances.

Finally, in prior-art D/A converters, when a 1 at a higher bit replaces all 1's of all lower bits, the design objective is for a voltage output to increase by a
15 voltage step 262 of FIGURE 11A. In contrast, in the present invention, a design objective is to produce a lower output voltage when a 1 for a higher bit replaces 1's for all lower bits, irrespective of resistor tolerances.

In some applications, such as learning systems, including the frequency-hopping oscillators 72 of FIGURE 4, 136 of FIGURE 6, 170 of
20 FIGURE 7, and 190 of FIGURE 8, the presence of holes in D/A converters 98 can cause the phase-locked oscillator 74, 152, 172, or 196 to "hunt." That is, at one input both the output voltage and the output frequency of the VCO 20 will be too low to phase lock, and at the very next higher input both an output voltage and a resultant output frequency of the VCO 20 will be too high.

While the voltage output of the D/A converter 282 is intentionally
25 nonlinear, it should be recognized that, in adaptive systems, such as the frequency-hopping oscillators 72, 136, 170 and 190, nonlinearity of components, such as the D/A converter 98, has no effect on the precision of the system. In contrast, holes in the voltage output can degrade preciseness of any
30 adaptive system seriously and even result in malfunction.

The D/A converter 282 of FIGURE 13 may be constructed with resistances of resistors R increased by resistances of resistors ΔR for all sixteen

bits 242. If so, resistors that are less precise than those commonly used in 12-bit D/A converters, and therefore more economical, can be used.

Or, since it is not particularly difficult or expensive to build 12-bit D/A converters that do not contain holes, the present invention may be practiced by custom manufacturing 16-bit, or greater, D/A converters in which only the higher bits include resistances that are equal to resistors R plus ΔR .

Referring now to FIGURE 16, a 16-bit nonlinear D/A converter 292 includes a 12-bit D/A converter 294 with twelve lower bits, or twelve binary inputs, 296, a 4-bit D/A converter 298 with four higher bits, or four higher binary inputs, 300, an analog scaler/summer 302, and an output node 304.

First, assume that the 16-bit nonlinear D/A converter 292 is an ideal D/A converter 240 as described in conjunction with FIGURE 9, and assume 65,536 volts as a digital 1 for the binary inputs, 296 and 300. Since there are 65,536 steps in a 16-bit D/A converter, each step would be 1.0 millivolt.

A maximum voltage output of the 12-bit D/A converter 294 occurs when all twelve inputs 296 are a binary 1. At this time, the input is 4,095. Therefore, the output voltage is 4,095 bits $\times$ 1.0 millivolt per bit = 4.095 volts.

When separate ones of the thirteenth, fourteenth, fifteenth, and sixteenth bits 300 are at a binary 1, the inputs are 4,096, 8,192, 16,384, and 32,768, respectively. Thus, it can be seen that each of the four higher binary inputs 300 doubles the voltage output.

It follows that, if the 12-bit D/A converter 294 produces less than 4.095 volts with all inputs at 1, there will be a hole when the binary input is increased by one, and a 1 at the thirteen bit 300 of the 4-bit D/A converter 298 replaces twelve bits 296 of the 12-bit D/A converter 294.

However, in the 16-bit nonlinear D/A converter 292 of FIGURE 16, an analog scaler/summer 302 is used to scale an output voltage in a output 304 of the 4-bit D/A converter 298 to any suitable value lower than 4.096 volts.

For instance, if the analog scaler/summer 302 decreases the steps produced by the 4-bit D/A converter 298 from 4.096 volts to 3.0 volts, as 3.0 volt increments are added to output voltages of the 12-bit D/A converter 294 that extend up to a maximum of approximately 4.095 volts, any possibility of holes in the four higher bits 300 is eliminated.

Instead of the possibility of any holes, there are duplicate digital addresses that will produce the same output voltages, similar to those shown and described in conjunction with FIGURE 11B.

In the example above, to reach any output voltage between 3.0 and 4.095, the 4-bit D/A converter 298 can have an output of either 0.0 or 3.0 volts. If the output of the 4-bit D/A converter 298 is 0.0 volts, the output of the 12-bit D/A converter 294 will range from 0.0 to 4.095 volts, but if the output of the 4-bit D/A converter 298 is 3.0 volts, the output of the 12-bit D/A converter 294 will range from 0.0 to 1.095 volts.

Referring now to FIGURE 17, a 16-bit nonlinear D/A converter 310 includes both a 12-bit D/A converter 312 of conventional design and a 4-bit D/A converter 314 of conventional design.

The 12-bit D/A converter 312 serves as the first twelve bits of the 16-bit nonlinear D/A converter 310, and the 4-bit D/A converter 314 serves as the thirteenth to sixteenth bits, so that the first bit of the 4-bit D/A converter 314 is the thirteenth bit of the 16-bit nonlinear D/A converter 310.

The 12-bit D/A converter 312 and the 4-bit D/A converter 314 are connected as shown by resistors R, 13.5R, and 27.0R, and a summing junction 316, where numbers associated with each resistor indicates its resistance in proportion to the other resistors.

The resistors R, 13.5R, and 27.0R provide a voltage summer, or proportional summer, 318, that proportionally sums output voltages of the 12-bit D/A converter 312 and the 4-bit D/A converter 314, producing at the summing junction 316, 1/15 of any output voltage of the 12-bit D/A converter 312, and 9/10 of any output voltage of the 4-bit D/A converter 314.

Therefore, assuming a 15.0 volt input, and assuming that the 12-bit D/A converter 312 is adjusted to produce 15.0 volts when all twelve inputs are 1's, 1.0 volts will be produced at the summing junction 316 and an output terminal 320.

Continuing to refer to FIGURE 17, when all twelve inputs are 1's, the input is 4,095. When the input increases by one to 4,096, all eleven of the inputs of the 12-bit D/A converter 312 go to 0's, and a first bit of the 4-bit D/A

converter 314, which is the thirteenth bit of the 16-bit nonlinear D/A converter 310, goes to a 1.

Assuming a 15.0 volt input to the 4-bit D/A converter 314, and assuming that the 4-bit D/A converter 314 is adjusted to produce 15.0 volts when all four inputs are 1's, the first bit of the 4-bit D/A converter 314 will produce 1/15 of 15.0 volts, or 1.0 volts. After being reduced as a factor of 9/10 by the proportional summer 318, 0.9 volts will be produced at the summing junction 316 and the output terminal 320.

Therefore, when an input is increased from 4,095, wherein all inputs are 1's, to an input of 4,096, wherein the first twelve inputs are 0's and the thirteenth input is a 1, an output voltage in the summing junction 316 and the output terminal 320 steps down from 1.0 to 0.9 volts, providing dual addresses as shown in FIGURE 12B.

A downward step 281 in the output voltages, as shown in FIGURE 12B, and developing of a dual address, repeats each time an input of the 12-bit D/A converter 312 changes from all 1's to all 0's, and an input of 4-bit D/A converter 314 increases by 1. Thus, for each of the fifteen digital inputs of the 4-bit D/A converter 314 there will be a downward step 281.

When all sixteen inputs of the 16-bit D/A converter 310 are 1's, the 12-bit D/A converter 312 produces 1/15 of 15.0 volts, or 1.0 volts at the summing junction 316. And the 4-bit D/A converter 314 produces 9/10 of 15.0 volts, or 13.5 volts at the summing junction 316. So with all sixteen inputs at 1's, the 16-bit D/A converter 310 produces 14.5 volts.

Referring now to FIGURE 18, a maximum output voltage of a conventional D/A converter is approximate 15.0 volts for an input of 15.0 volts, as shown by a linear output voltage curve 324. The linearity of the curve 324 can be seen in the fact that the curve 324 intersects corners 326 of grids 328.

Referring now to FIGURE 19, even though downward steps 330, as labeled in FIGURE 19A, are only 0.1 volts for each of the digital addresses of the 4-bit D/A converter 314, in a nonlinear output voltage curve 332 of FIGURE 19, the magnitude of downward steps 330 is exaggerated for the purpose of clearly illustrating nonlinearity. The fact that the output voltage curve 332 of FIGURE 19 is nonlinear can be seen by the fact that the curve 332

progressively falls farther below corners 326 that are aligned with a phantom line 334.

Referring now to FIGURE 20, if the 12-bit D/A converter 312 were adjusted to produce 1.1 volts at the summing junction 316 in response to a binary input of twelve 1's, and the 4-bit D/A converter 314 were adjusted to produce 1.0 volts at the summing junction 316 for each of the fifteen inputs that are possible with four bits, the downward steps 330 would occur in response to all fifteen inputs as in FIGURE 19, but an output voltage curve 336 would slope upward somewhat more steeply, rising slightly over successive ones of the corners 326, and stepping downward to successive ones of the corners 326.

As described in conjunction with FIGURE 20, since the 4-bit D/A converter 314 will produce 1.0 volts for each of the fifteen numerical inputs for a total of 15.0 volts, and the 12-bit D/A converter 312 will produce 1.1 volts when all twelve inputs are 1's, the maximum output voltage will be 16.1 volts, very close to the output voltage of a conventional D/A converter with a 15.0 volt input.

However, even though the output voltage curve 336 approximates linearity, it is nonlinear, because of the downward steps 330.

In the 16-bit D/A converter 310 of FIGURE 17, and in the embodiments of FIGURES 21 and 22, which will be described subsequently, the downward steps 330 are designed to be sufficiently large that they, and the aforementioned characterizing features of the present invention, are maintained consistently in production lots of nonlinear D/A converters irrespective any normal variations in resistor or other component tolerances, and in spite of any normal accumulation of tolerances, in all bits designed to include the downward steps 330.

Referring now to FIGURE 21, a 16-bit nonlinear D/A converter 340 includes a 12-bit D/A converter 342 with inputs Q0 to Q11 that correspond to bits 1-12, a 4-bit D/A converter 344, as indicated by a like-numbered phantom line, that includes inputs Q12 to Q15 that correspond to bits 13-16, a current summer 346, and a resistor 5R.

The 4-bit D/A converter 314 includes resistors 5.55 R, 2.77R, 1.39R, and 0.69R that are connected to a summing junction 348, as shown. The numbers associated with each resistor indicates the relative resistance, one with another.

5 The current summer 346 includes an summer/inverter 350 and an inverter 352. The summer/inverter 350 includes an operational amplifier 354. The summer/inverter 350 includes an operational amplifier 354 and a feedback resistor R1. The inverter 352 includes an operational amplifier 356 and a feedback resistor R2. The operational amplifiers, 354 and 356, are connected
10 by a resistor R3, where the suffix numbers, 1, 2, and 3, distinguish individual resistors of equal resistances. The operational amplifiers, 354 and 356, are connected to positive and negative source voltages, as shown.

First, assume that: all inputs, Q0 to Q11, of the 12-bit D/A converter 342 are all 1's with a 5.0 volt dc reference, inputs Q12 through Q15 of the 4-bit D/A converter 344 are at 0.0 volts dc and open, and a voltage in an output
15 conductor 358 of the 12-bit D/A converter 342 is +5.0 volts dc.

However, since a resistor 5R is interposed between the 12-bit D/A converter 342 and the summing junction 348, the gain of the summer/inverter 350 is $1R/5R$ or 0.2, so that 1.0 volts dc is fed to the inverting input of the operational amplifier 354. After being inverted by the summer/inverter 350,
20 and again being inverted by the inverter 352, +1.0 volts dc is produced at an output terminal 360.

For this output of +1.0 volts dc, the numerical input was 4,095. Increasing the input to 4,096 changes all twelve inputs Q0 to Q11 of the 12-bit D/A converter 342 to 0.0 volts and open, and changes Q12 of the 4-bit D/A
25 converter 344 to 1.

Assuming a +5.0 volt dc input to Q12, the gain of the summer/inverter 350, with respect to Q12 is 0.18, so the summer/inverter 350 outputs a negative 0.9 volts, which, after a second inverting by the inverter 352, produces
30 +0.9 volts in the output conductor 358.

Therefore, referring again to FIGURE 19A, a downward step 330 of 0.1 volts is provided from a change in input from 4,095 to 4096, which is identical to that described in conjunction with FIGURE 17.

In like manner, every time twelve 1's at Q0 through Q11 are replaced by twelve 0's, a downward step 330 of 0.1 volts is developed, thereby producing dual addresses as shown in FIGURE 12B.

When inputs Q12 to Q15 are all at a binary 1, the parallel-connected resistors 5.55R, 2.77R, 1.39R, and 0.69R, and +13.5 volts is produced at the output terminal 360. And, when all inputs, Q0 through Q15 are a binary 1, the 12-bit D/A converter 342 adds 1.0 volts, as described above, so that the 16-bit nonlinear D/A converter 340 produces a maximum output of 14.5 volts which is identical to the maximum output voltage for the embodiment of FIGURE 17

Referring now to FIGURE 22, a 16-bit nonlinear D/A converter 370 includes a 12-bit inverting D/A converter 372, a 4-bit inverting D/A converter 374, a proportional summer, or current summer 376, a summing junction 378, and a resistor 7.2R.

The current summer 376 includes an operational amplifier 380 that is connected to a positive source and to ground, as shown, a feedback resistor 1.44R, and an input to the positive input terminal of 3.718 volts.

The 12-bit inverting D/A converter 372 includes the 12-bit D/A converter 342 of FIGURE 12 and a 12-bit inverter 382. The 4-bit inverting D/A converter 374 includes a 4-bit D/A converter 384 and a 4-bit inverter 386. The 4-bit D/A converter 384 includes resistors 8R, 4R, 2R, and R, where the prefix numbers indicate relative resistances.

While, optionally, the 12-bit inverter 382 and the 4-bit inverter 386 may be eliminated, the resultant device would function with negative logic.

First assume a source of 5.0 volts dc. For an input of 4,095, inputs Q0 through Q11 are 1's, the output of the 12-bit D/A converter 372 decreases from 5.0 volts to 0.0 volts, and an output of the proportional summer 376, at an output terminal 388, increases from 0.0 to 1.0 volts due to the 0.2 times inverting gain of the proportional summer 376.

When the input is increased from 4,095 to 4,096, inputs Q0 through Q11 go to 0's, and Q12 goes to a 1. At this time, inputs Q0 through Q11 do not provide any output voltage to the output terminal 388. However, with 5.0

volts applied to Q12, the output of the proportional summer 376 to go to 0.9 volts.

Therefore, as also described for the embodiments of FIGURES 17 and 21, the 16-bit nonlinear D/A converter 370 provides downward steps 330 of 0.1 volts, as shown in FIGURE 19, 19A, and 20, each time Q0 through Q11 go to 0's, and an input to Q12 through Q15 increases by 1. Since a 4-bit D/A converter 384 has fifteen inputs that are 1's, fifteen downward steps 330 are produced. And, as also described in conjunction with FIGURES 17 and 21, the 16-bit nonlinear D/A converter 370 of FIGURE 22 provides a maximum output of 14.5 volts when all sixteen inputs, Q0 through Q15, are 1's.

In the preceding descriptions, the outputs of the 4-bit D/A converters, 314, 344, and 374 have been reduced to produce the downward steps 330. Optionally, the outputs of the 12-bit D/A converters 312, 342, and 372 may be increased as taught in conjunction with FIGURE 20, thereby, at least partially, providing the downward steps 330 by increasing outputs of the 12-bit D/A converter 312, 342, or 372.

Referring again to FIGURES 16, 17, 21, and 22, outputs of two D/A converters are proportionally summed. In the embodiment of FIGURE 17, the D/A outputs are voltage summed, and in the embodiments of FIGURES 21 and 22, the D/A outputs are current summed.

In any of the embodiments of the nonlinear D/A converters taught herein, even if low quality resistors are used, if voltage outputs are scaled as taught herein, D/A converters can be constructed with any desired number of bits without any danger of holes existing in output voltages.

Referring again to FIGURE 13, alternately, rather than changing resistances of resistors R and/or 2R, input voltages to some of the higher bits 242 can be scaled.

Adaptive learning systems that utilize a D/A converter can practice the present invention by scaling output voltages for some of the higher bits, or all of the bits, by any of the means taught herein.

In summary, the nonlinear D/A converters 282, 292, 310, 340, and 370 of the present invention can be characterized by method steps as: being intentionally nonlinear; preventing holes; providing dual addressees; making a

voltage output of one bit less than twice the next lower bit; making an output voltage of a higher bit less than a total output voltage of all lower bits; making an output voltage of one numerical input greater than an output voltage of the next higher numerical input; and/or interjecting downward steps 281 and 330; all irrespective of random component variables that may occur at the time of production, or subsequently during use.

Referring now to FIGURE 23, a digital sample-and-hold device, or adaptive learning system, 400 includes a comparator 402 that is connected to a SET terminal of a bistable multivibrator 404 by a set conductor 406, an oscillator, or clock, 408 that is connected to the bistable multivibrator 404 by an inhibit conductor 410, a 16-bit binary counter 412 that is connected to the oscillator 408 by a clock conductor 414, and the 16-bit nonlinear D/A converter 310 of FIGURE 17.

The 16-bit nonlinear D/A converter 310 of FIGURES 17 and 23 includes the 12-bit D/A converter 312, the 4-bit D/A converter 314, and the proportional summer 318. As shown in FIGURE 23, bits Q_0 to Q_{11} of the 12-bit D/A converter 312 are connected to the 16-bit binary counter 412 by a 12-bit data bus 416, and bits Q_{12} to Q_{15} of the 4-bit D/A converter 314 are connected to the 16-bit binary counter 412 by a 4-bit data bus 418.

The proportional summer 318 includes the resistors, R , $13.5R$, and $27.0R$ that are connected to each other at the summing junction 316. The resistor $13.5R$ is connected to the 12-bit D/A converter 312 by a conductor 420, the resistor R is connected to the 4-bit D/A converter 314 by a conductor 422, and the resistor $27.0R$ is connected to ground, as shown.

Output voltages from the 12-bit D/A converter 312 and the 4-bit D/A converter 314 are proportionally summed at the summing junction 316 as described in conjunction with FIGURE 17.

The proportionally-summed voltage is fed back from the summing junction 316 to the comparator 402 by a feedback conductor 424, and is delivered to the output terminal 320 by an output conductor 426.

A sample-voltage conductor 428 connects a V_{IN} terminal to a positive input terminal of the comparator 402, and a sample-command conductor 430

connects a V_s terminal to a RESET terminal of the bistable multivibrator 404 and to a RESET terminal of the 16-bit binary counter 412.

In operation, an analog voltage that is to be sampled and held is applied to the positive input terminal of the comparator 402 via the sample-voltage conductor 428. A sample command, in the sample-command conductor 430, resets both the bistable multivibrator 404 and the 16-bit binary counter 412. When the sample command is removed, the oscillator 408 begins sending out clock pulses, thereby incrementing the 16-bit binary counter 412.

The 16-bit D/A binary counter 412 outputs binary-coded numbers to the 12-bit D/A converter 312, and the 12-bit D/A converter 312 outputs a proportional and increasing voltage to the proportional summer 318 via the conductor 420 until the count of the binary counter 412 is a binary-coded 4,095.

At the count of 4,096, the output voltage of the 12-bit D/A converter 312 drops to zero, the 4-bit D/A converter 314 outputs a voltage that is proportional to the count of 4,096, and the proportional summer 318 reduces the output voltage of the 4-bit D/A converter 314 by a predetermined ratio at the summing junction 316. This reduction in the output voltage produces the downward steps 330, as shown in FIGURES 19 and 20, as described in conjunction with FIGURE 17.

As the oscillator 408 continues to clock the 16-bit binary counter 412, the count continues to increase, the 12-bit D/A converter 312 and the 4-bit D/A converter 314 continues to increase the voltage at the summing junction 316 and in the feedback conductor 424, except for downward steps 330 each time one bit in the 4-bit D/A converter 314 replaces 12 bits in the 12-bit D/A converter 312, until the voltage applied to the negative input of the comparator 402 equals the voltage in the sample-voltage conductor 428.

While the digital sample-and-hold device 400 has been shown and described using the 16-bit nonlinear D/A converter 310 of FIGURE 17, any D/A converter that produces a plurality of the downward steps 330 may be used, including the D/A converters 282, 292, 340, and 370 of FIGURES 13, 16, 21, and 22, respectively.

The sample-and-hold device 400 includes therein, as a subcombination, a nonlinear analog-to-digital (A/D) converter 432. The nonlinear A/D converter 432 includes the comparator 402, the oscillator 408, the 16-bit binary counter 412, and a nonlinear D/A converter, such as the 16-bit nonlinear D/A converter 310. The analog input of the nonlinear A/D converter 432 is V_{IN} , and the digital output is the binary-coded output of the 16-bit binary counter 412.

A learning path 434 of the sample-and-hold device 400, and also of the nonlinear A/D converter 432 that is a subcombination of the sample-and-hold device 400, includes the comparator 402, the oscillator 408, the 16-bit binary counter 412, the 16-bit nonlinear D/A converter 310, and the feedback conductor 424.

Referring now to FIGURE 24, a digital follow-and-hold device, or adaptive learning system, 440 includes components and conductors that are like-named and like-numbered with those of FIGURE 23, except as otherwise named and numbered.

More particularly, the digital follow-and-hold device 440 includes a delay 442, the oscillator 408, a 16-bit UP/DOWN counter 444, and the 16-bit nonlinear D/A converter 310 with the 12-bit D/A converter 312, the 4-bit D/A converter 314, and the proportional summer 318 thereof.

The digital follow-and-hold device 440 also includes an analog follow-and-hold device 446 that includes a field-effect transistor, or FET, 448 and a capacitor 450. The analog follow-and-hold device 446 is effective to follow, and to temporarily hold a voltage applied thereto from V_{IN} .

In operation, with a FOLLOW signal in a follow/hold conductor 452, the FET 448 is in a conducting mode, and the voltage of V_{IN} is applied to the capacitor 450 of the analog follow-and-hold device 446 by conductors 454 and 456.

At this time, the oscillator 408 is clocking the 16-bit UP/DOWN counter 444 via the clock conductor 414. The UP/DOWN counter 444 increments or decrements in accordance with either an UP signal or a DOWN signal produced by the comparator 402 and delivered to the 16-bit UP/DOWN counter 444 by an up/down conductor 458. That is, an UP signal is produced when the 16-bit D/A converter 310 is producing a voltage that is lower than

that applied to the positive input terminal of the comparator 402 by the capacitor 450 through the conductor 456.

5 When a HOLD signal is received in the follow/hold conductor 452, a gate conductor 460 causes the FET 448 to change to a nonconducting state, so that the analog follow-and-hold device 446 temporarily holds the voltage of V_{IN} as it was when the HOLD signal was received.

10 After a predetermined time delay, the delay 442 sends an INHIBIT signal to the oscillator 408 via the inhibit conductor 410, the oscillator 408 ceases clocking the UP/DOWN counter 444, and the count of the UP/DOWN counter 444 is frozen.

15 The time delay of the delay 442 allows the oscillator 408, the UP/DOWN counter 444, and the 16-bit nonlinear D/A converter 310 to increase or decrease the voltage in the feedback conductor 424 that is applied to the negative input terminal of the comparator 402 to equal the voltage that is being applied to the positive input terminal of the comparator 402 by the capacitor 450.

20 In addition, the time delay of the delay 442 allows the oscillator 408 and the UP/DOWN counter 444 to correct for any error that might occur because of the downward steps 330, as shown in FIGURES 19 and 20, in the output voltage of the 16-bit nonlinear D/A converter 310.

25 That is, if while incrementing, the count of the 16-bit UP/DOWN counter 444 were to stop at a count that produces one of the downward steps 330, the output voltage in the feedback conductor 424 would drop 0.1 volts, leaving the output voltage in the terminal 320 0.1 volts lower than that held by the capacitor 450 and applied to the positive input terminal of the comparator 402.

30 However, an INHIBIT signal is not applied to the oscillator 408 until a predetermined time delay, as determined by the delay 442, and the oscillator continues to clock the UP/DOWN counter 444, thereby providing time for the follow-and-hold device 440 to compensate for a downward step 330.

In like manner, if while decrementing, the count of the 16-bit UP/DOWN counter 444 were to stop at a count just lower than that which produces one of the downward steps 330, the output voltage in the feedback

conductor 424 would jump 0.1 volts, leaving the output voltage in the terminal 320 0.1 volts higher than that held by the capacitor 450 and applied to the positive input terminal of the comparator 402.

5 But the INHIBIT signal is not applied to the oscillator 408 until a predetermined time delay, as determined by the delay 442, and the oscillator continues to clock the UP/DOWN counter 444, thereby providing time for the follow-and-hold device 440 to compensate for the sudden increase in output voltage that is produced by backing over a downward step 330.

10 Finally, the follow-and-hold device 440 includes therein, as a subcombination, a nonlinear analog-to-digital (A/D) converter 462. The nonlinear A/D converter 462 includes the comparator 402, the oscillator 408, the 16-bit UP/DOWN counter 444, and a nonlinear D/A converter, such as the 16-bit nonlinear D/A converter 310. The analog input of the nonlinear A/D converter 462 is V_{IN} , and the digital output is the binary-coded output of the 16-bit UP/DOWN counter 444.

15 A learning path 464 of the follow-and-hold device 440, and also of the nonlinear A/D converter 460 that is a subcombination of the follow-and-hold device 440, includes the comparator 402, the oscillator 408, the 16-bit UP/DOWN counter 444, the 16-bit nonlinear D/A converter 310, and the feedback conductor 424.

The present invention provides adaptive learning devices, such as adaptive frequency-hopping oscillators, phase-locked oscillators, sample-and-hold devices, follow-and-hold devices, and A/D converters that, at least optionally, use the nonlinear D/A converters of the present invention.

25 While specific apparatus and method have been disclosed in the preceding description, and while part numbers have been inserted parenthetically into the claims to facilitate understanding of the claims, it should be understood that these specifics have been given for the purpose of disclosing the principles of the present invention and that many variations thereof will become apparent to those who are versed in the art. Therefore, the scope of the present invention is to be determined by the appended claims, and without 30 any limitation by the part numbers inserted parenthetically in the claims.

INDUSTRIAL APPLICABILITY

The present invention is applicable to oscillators, transmitters, receivers, and adaptive learning devices, such as adaptive frequency-hopping oscillators, sample-and-hold devices, follow-and hold-devices, and A/D converters, and to D/A converters.

CLAIMS

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A learning system (72, 136, 170, 190, 400, or 440) having a learning
5 path (222, 224, 226, 228, 434, or 464) with a D/A converter that produces an output voltage as a function of a binary input, the improvement in which:
said D/A converter comprises a nonlinear D/A converter (282, 292, 310, 340, or 370) that produces a plurality of downward steps (281 or 330) in said output voltage; and
10 said downward steps are sufficiently large that manufacturing tolerances cannot obliterate any of them.
2. A method for producing channelized output frequencies which comprises:
a) recalling previously stored channelizing information for one of said
15 channels;
b) repeatedly correcting said recalled channelizing information before recalling previously stored channelizing information for an other channelized frequency; and
c) interposing storing and driving steps intermediate of said repeatedly
20 correcting steps.
3. A method for producing channelized output frequencies, which method comprises recalling previously stored channelizing information for one of said channels, driving an output frequency toward phase lock for said one channel, and comparing a feedback frequency with a reference frequency for
25 said channelized output frequency, the improvement which comprises:
a) correcting said recalled channelizing information in response to said comparing step;
b) storing said corrected channelizing information subsequent to said correcting step;

c) driving said output frequency closer to phase lock in response to said correcting step; and

d) repeating said correcting, driving, and storing steps before changing to an other of said channelized frequencies.

5 4. A method for phase locking an output frequency which comprises D/A converting binary-coded information into an output voltage, the improvement in which said D/A converting step comprises:

 a) producing a plurality of downward steps in said output voltage; and
 b) preventing manufacturing tolerances from obliterating any of said
10 downward steps.

 5. A method for converting binary-coded inputs into an output voltage that varies as function of said binary-coded information, the improvement which comprises:

 a) producing a plurality of downward steps in said output voltage; and
15 b) preventing manufacturing tolerances from obliterating any of said downward steps.

 6. A method which comprises clocking, counting, D/A converting, and comparing, the improvement which comprises:

 a) producing a plurality of downward steps in an output voltage
20 produced by said D/A converting; and
 b) preventing manufacturing tolerances from obliterating any of said downward steps.

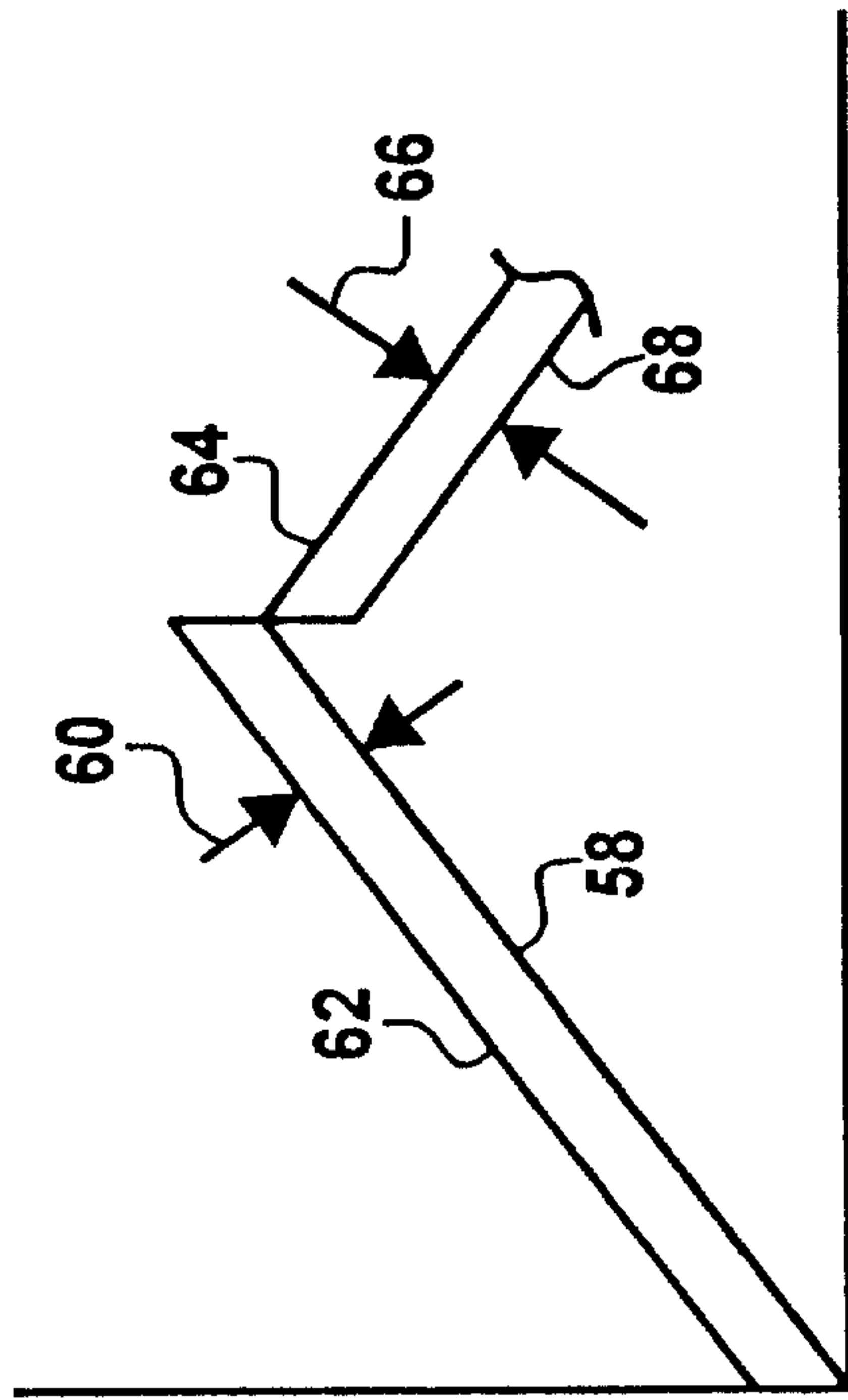
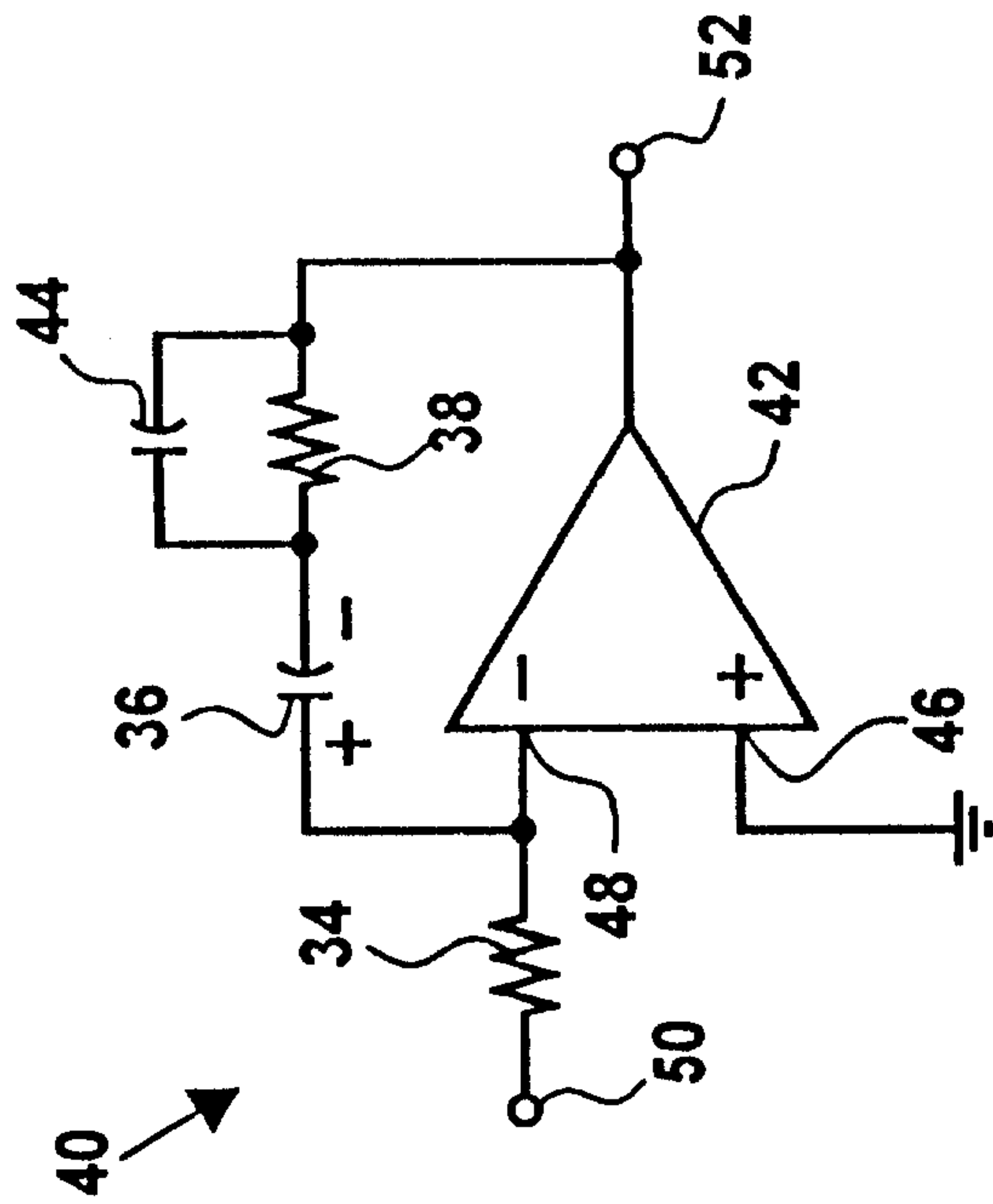
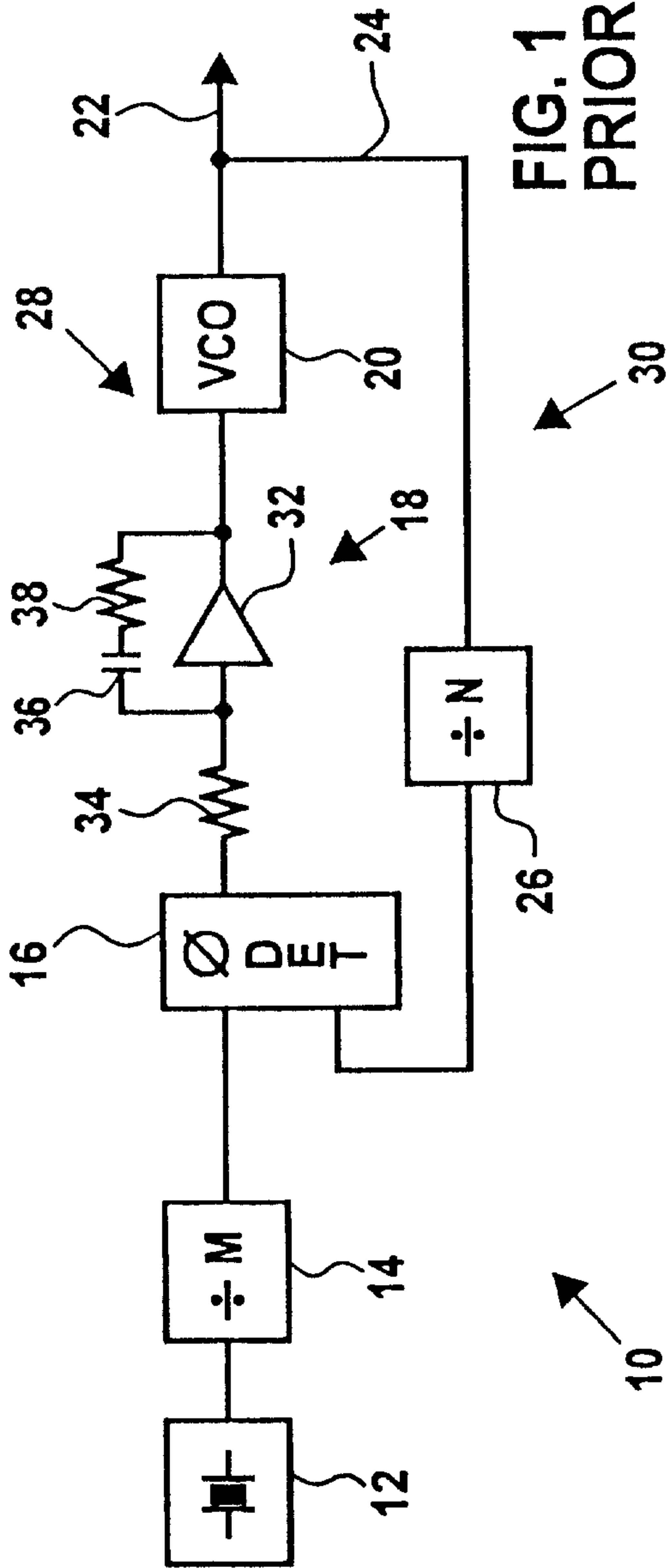
 7. A method for sampling and digitally holding an analog voltage comprises resetting, clocking, binary counting, D/A converting, and comparing,
25 the improvement which comprises:

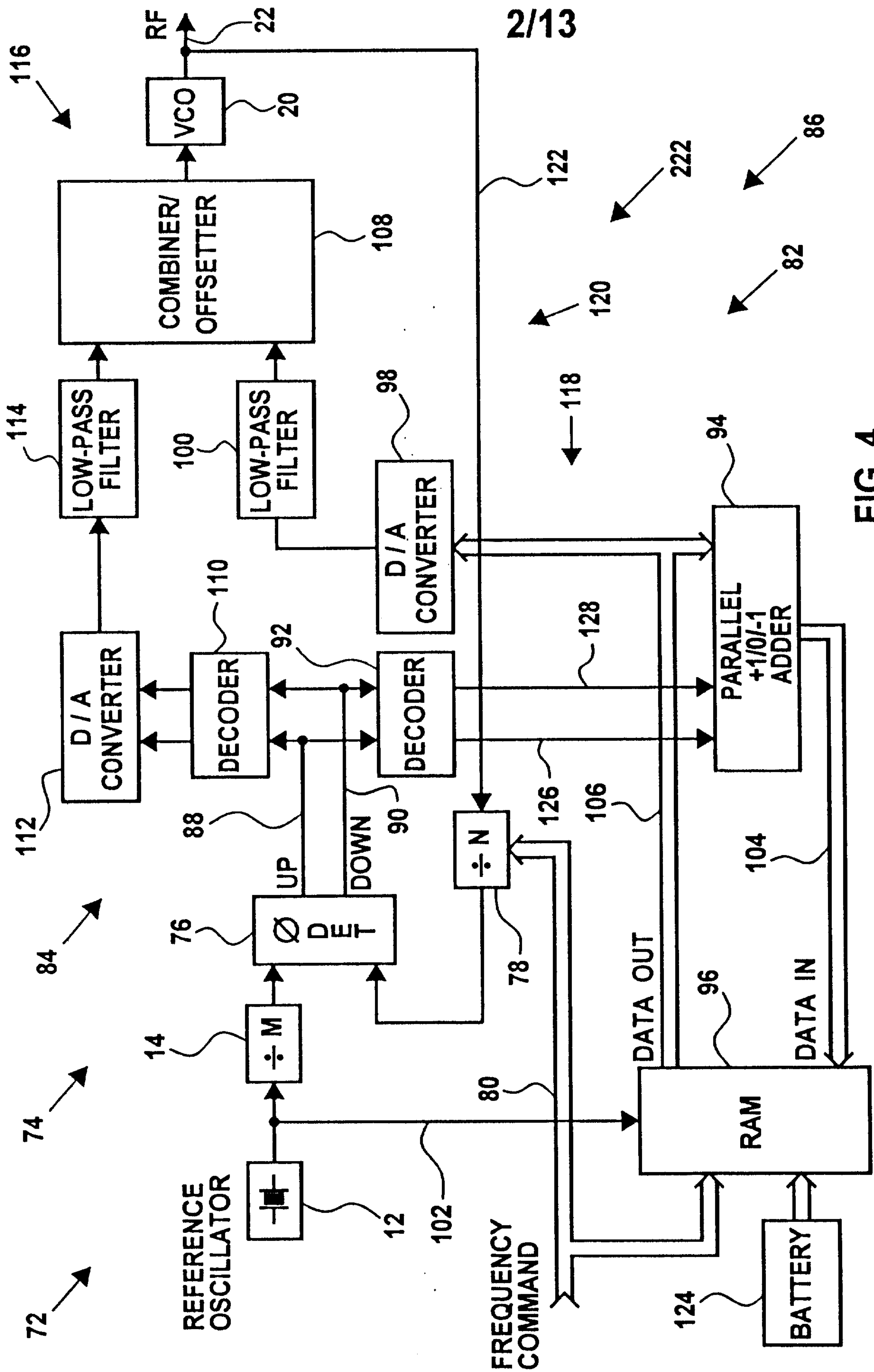
 a) producing a plurality of downward steps in an output voltage produced by said D/A converting; and
 b) preventing manufacturing tolerances from obliterating any of said downward steps.

8. A method for following and digitally holding an analog voltage comprises analog following, analog holding, clocking, UP/DOWN counting, D/A converting, and comparing, the improvement which comprises:

- a) producing a plurality of downward steps in an output voltage
5 produced by said D/A converting;
- b) preventing manufacturing tolerances from obliterating any of said downward steps;
- c) correcting for errors produced by said downward steps; and
- d) said correcting step comprises continuing said counting subsequent
10 to said analog holding.

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Patent Agents**





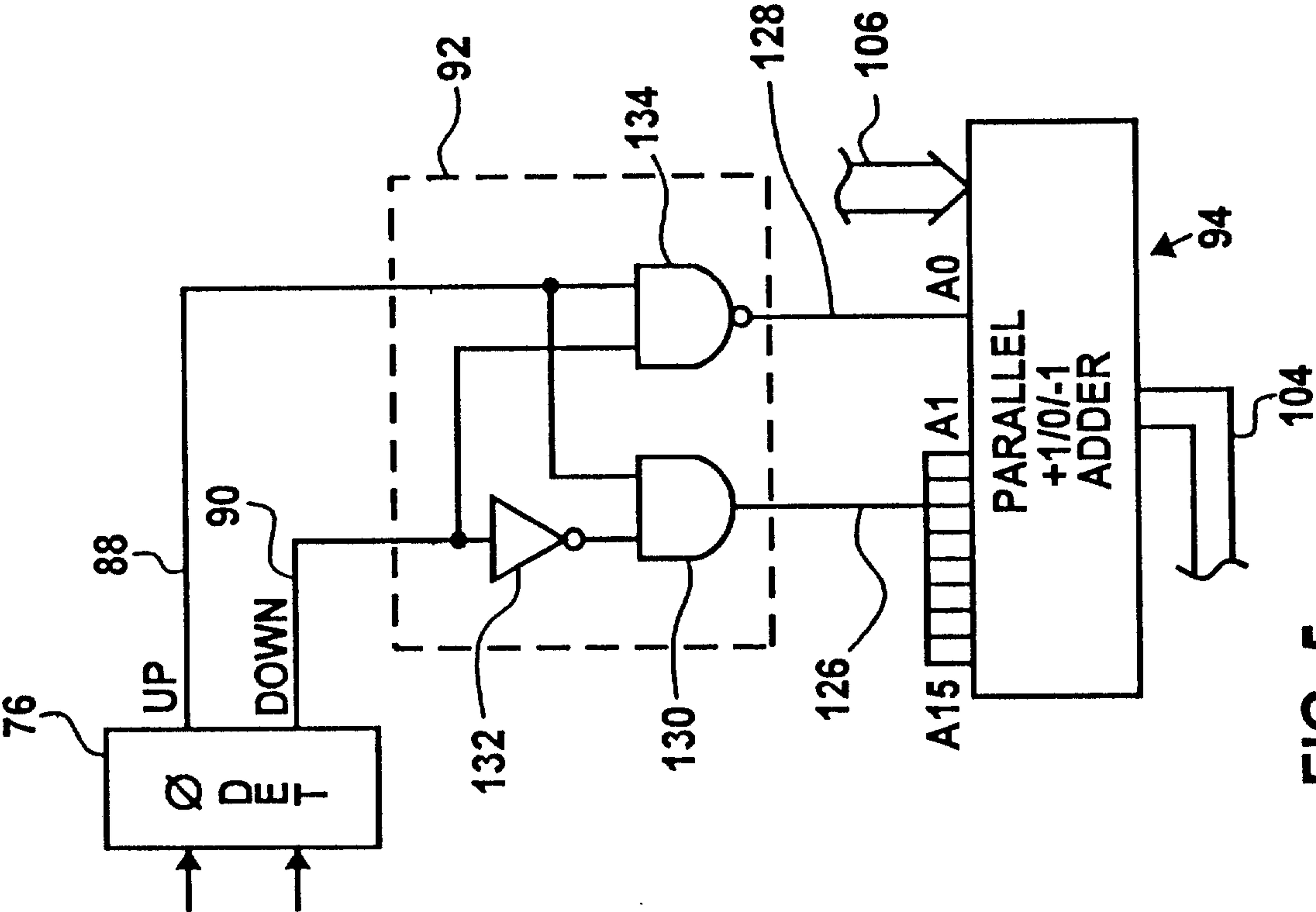


FIG. 5

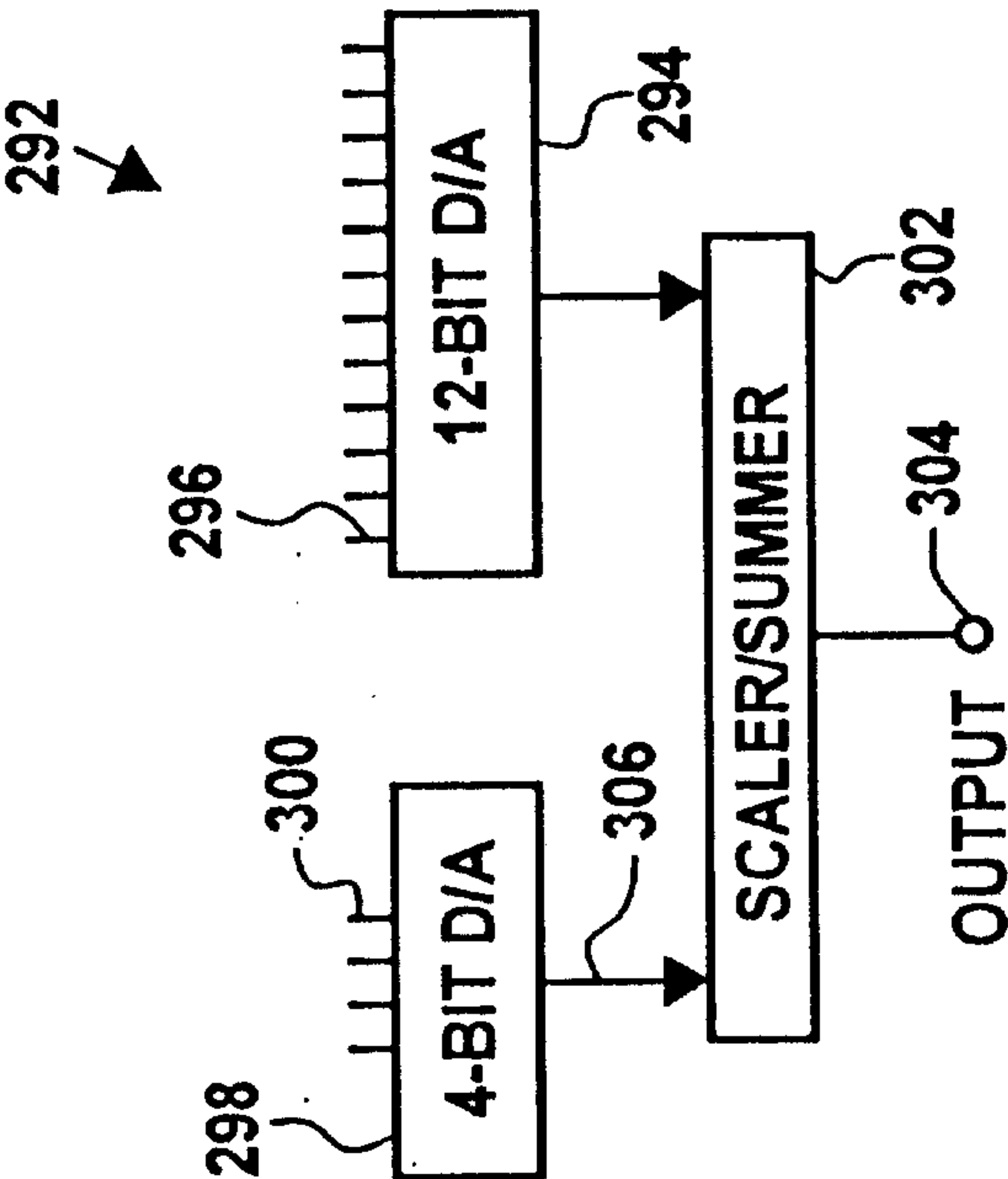


FIG. 16

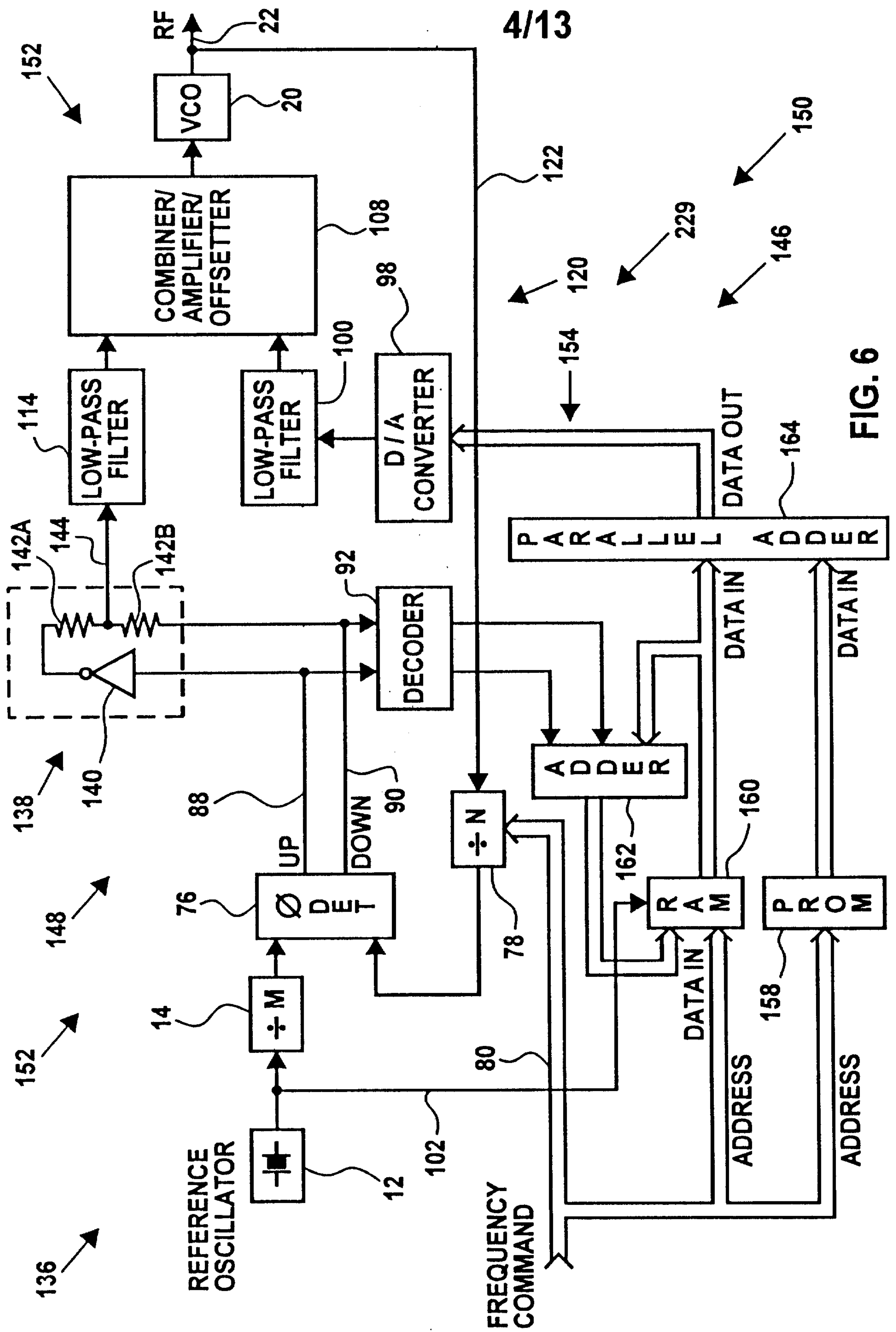


FIG. 6

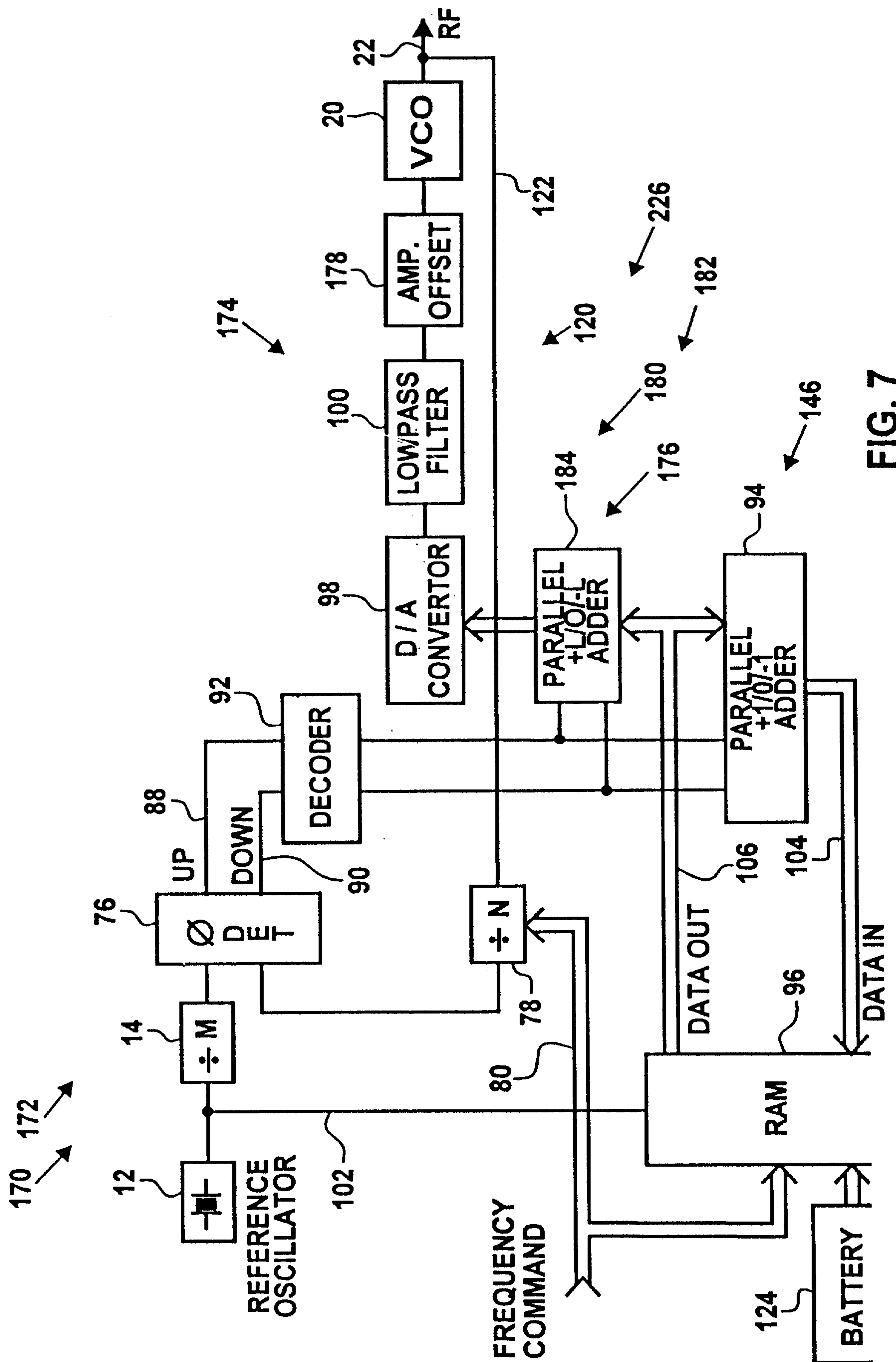


FIG. 7

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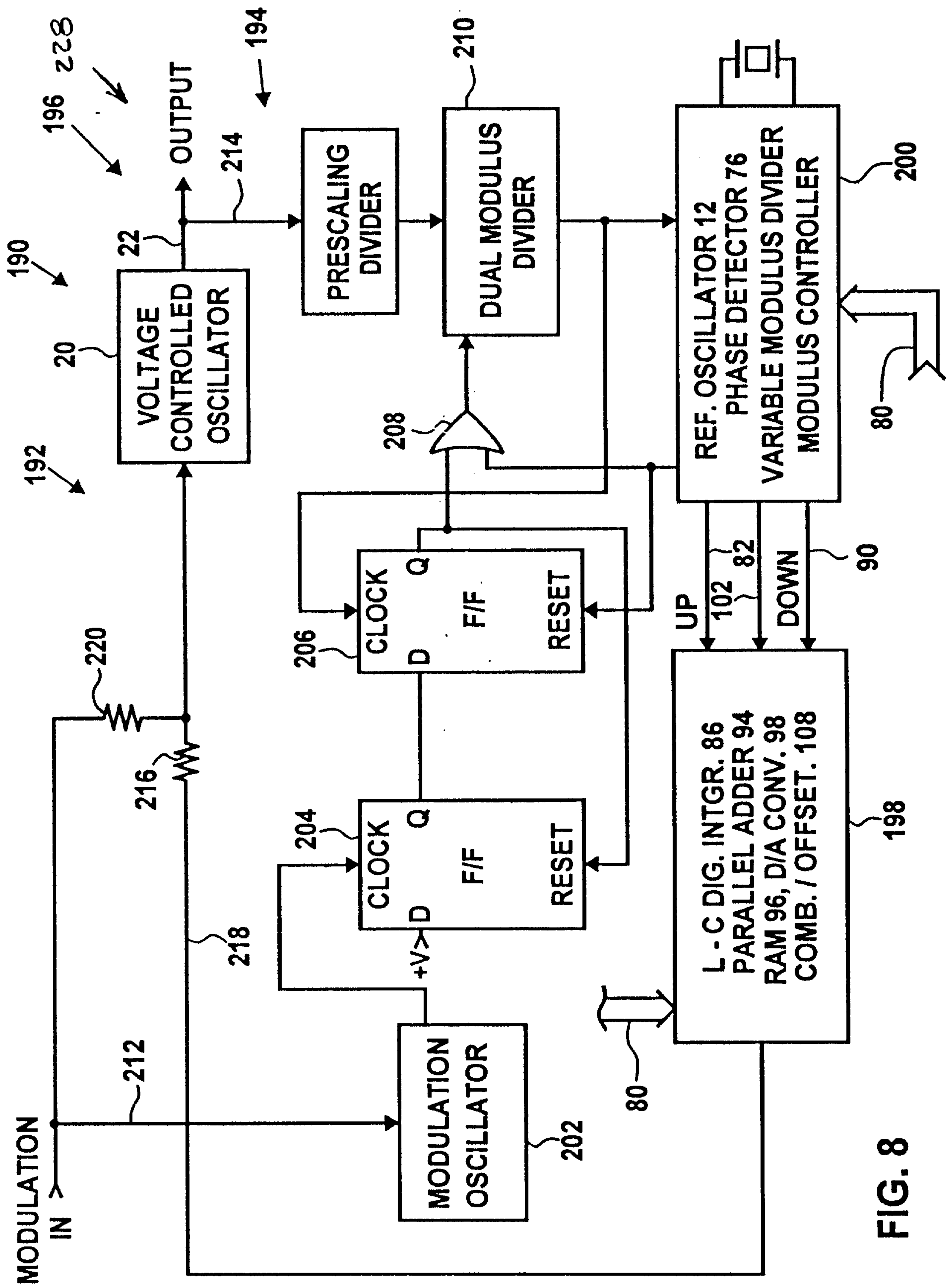
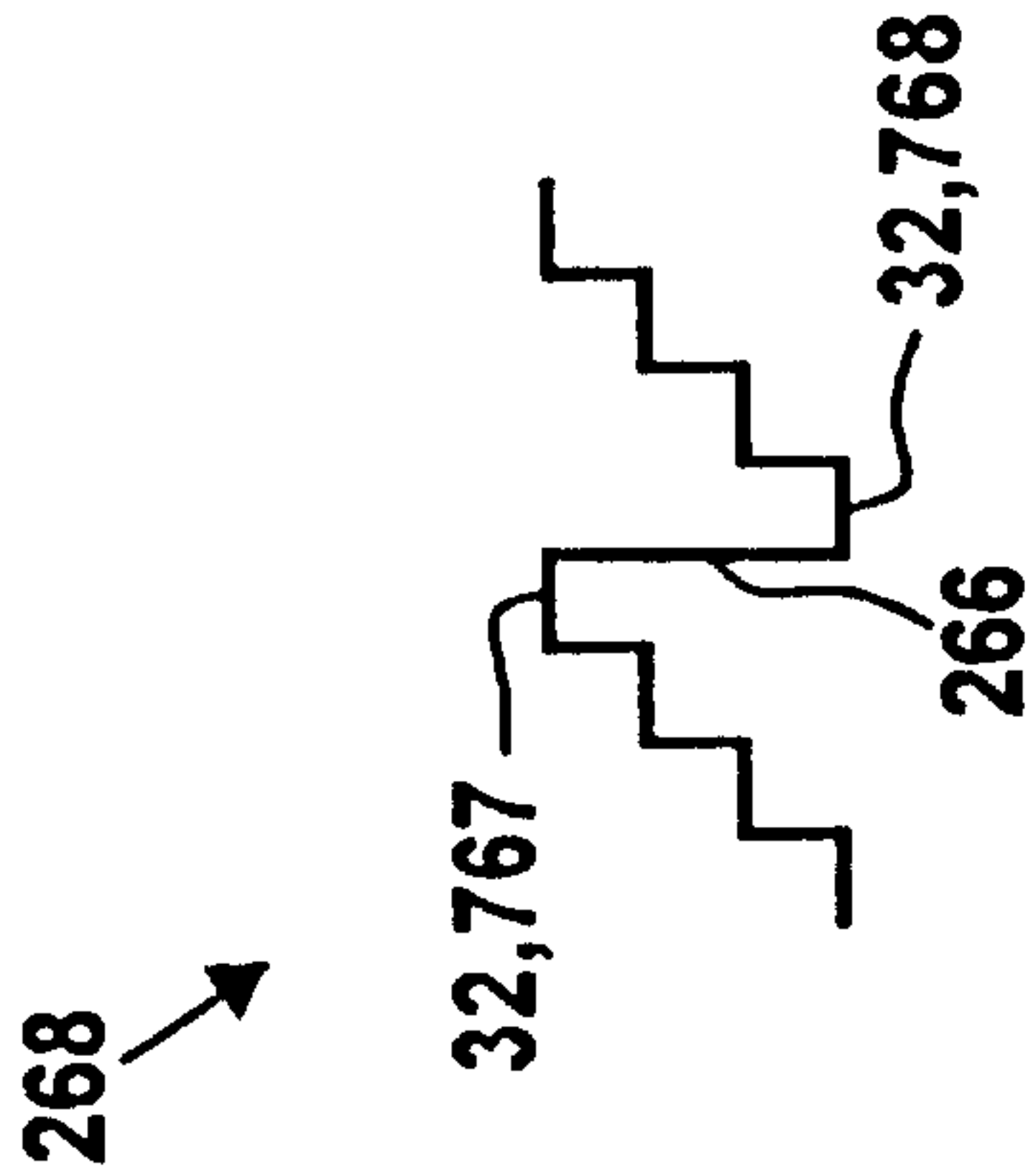
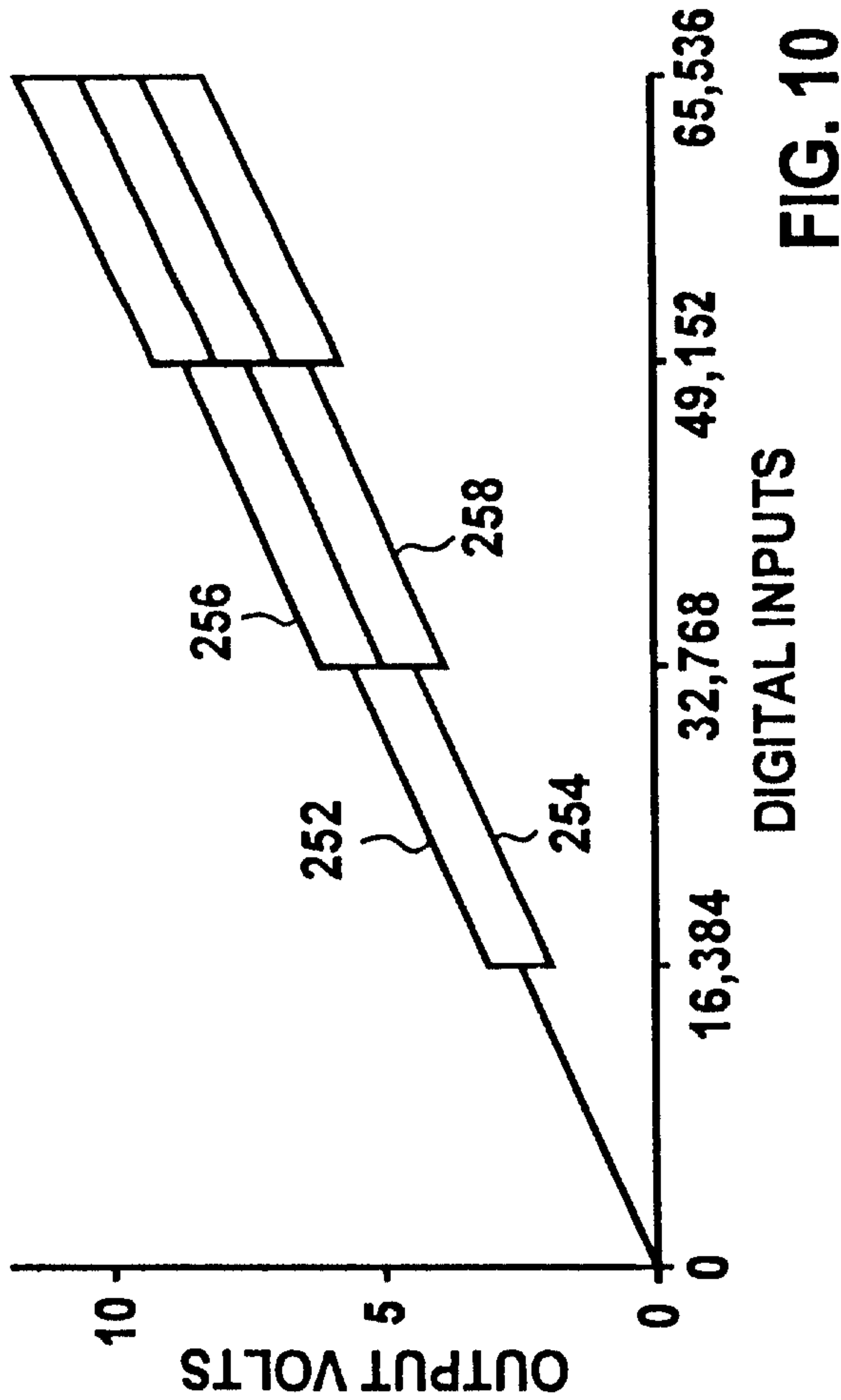
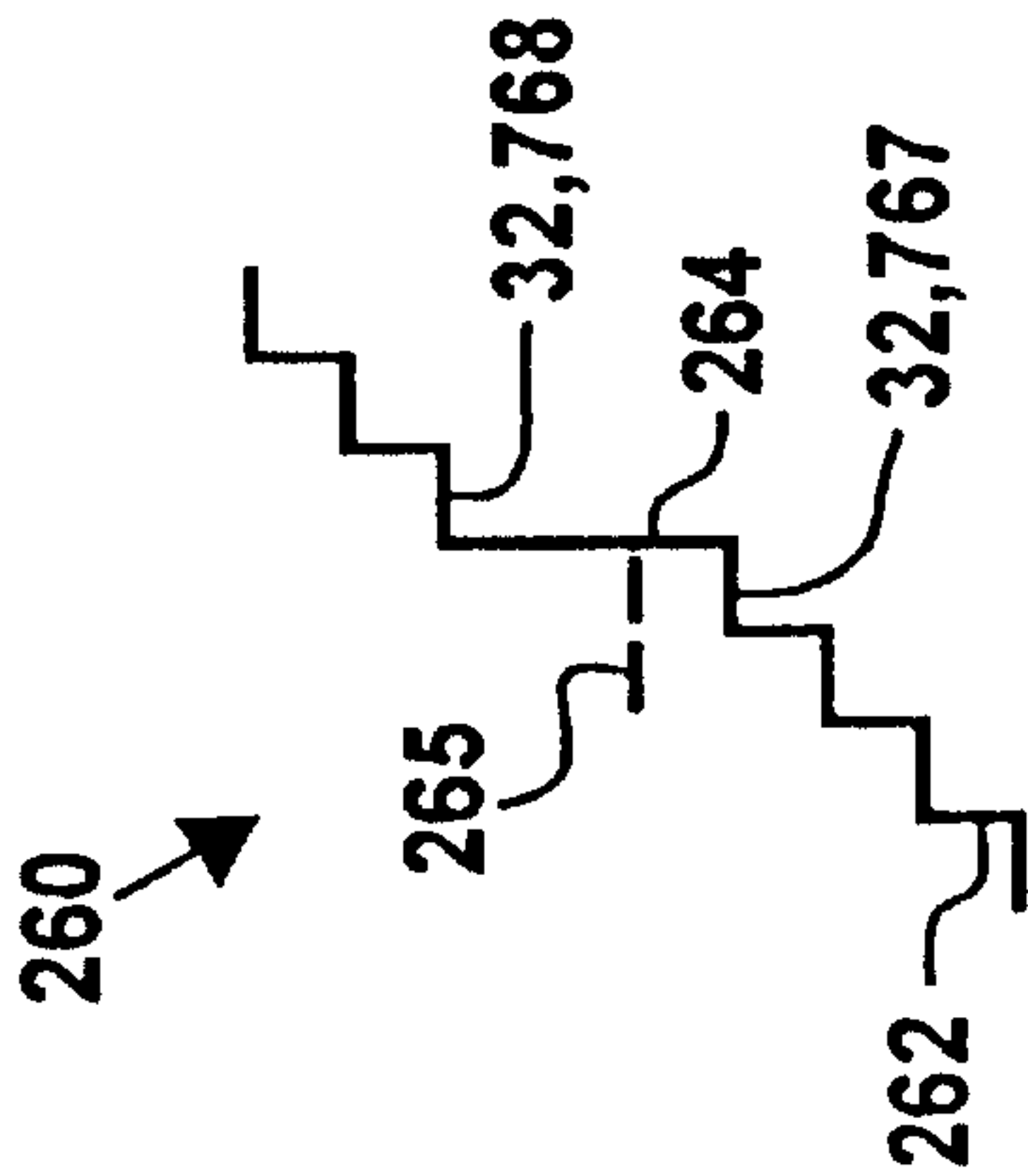
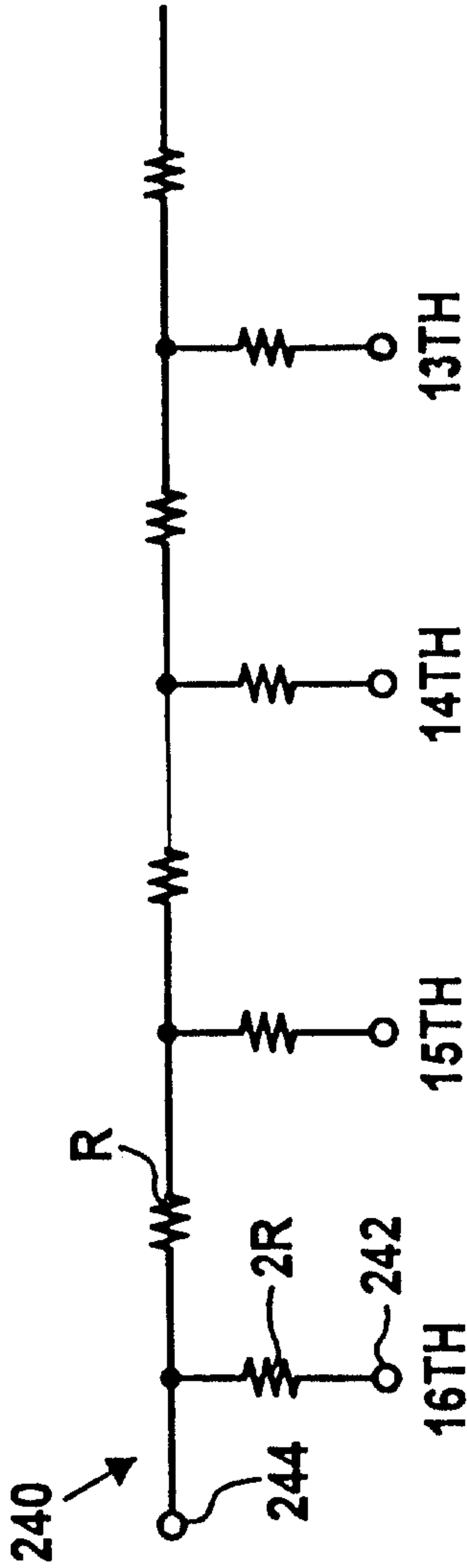


FIG. 8



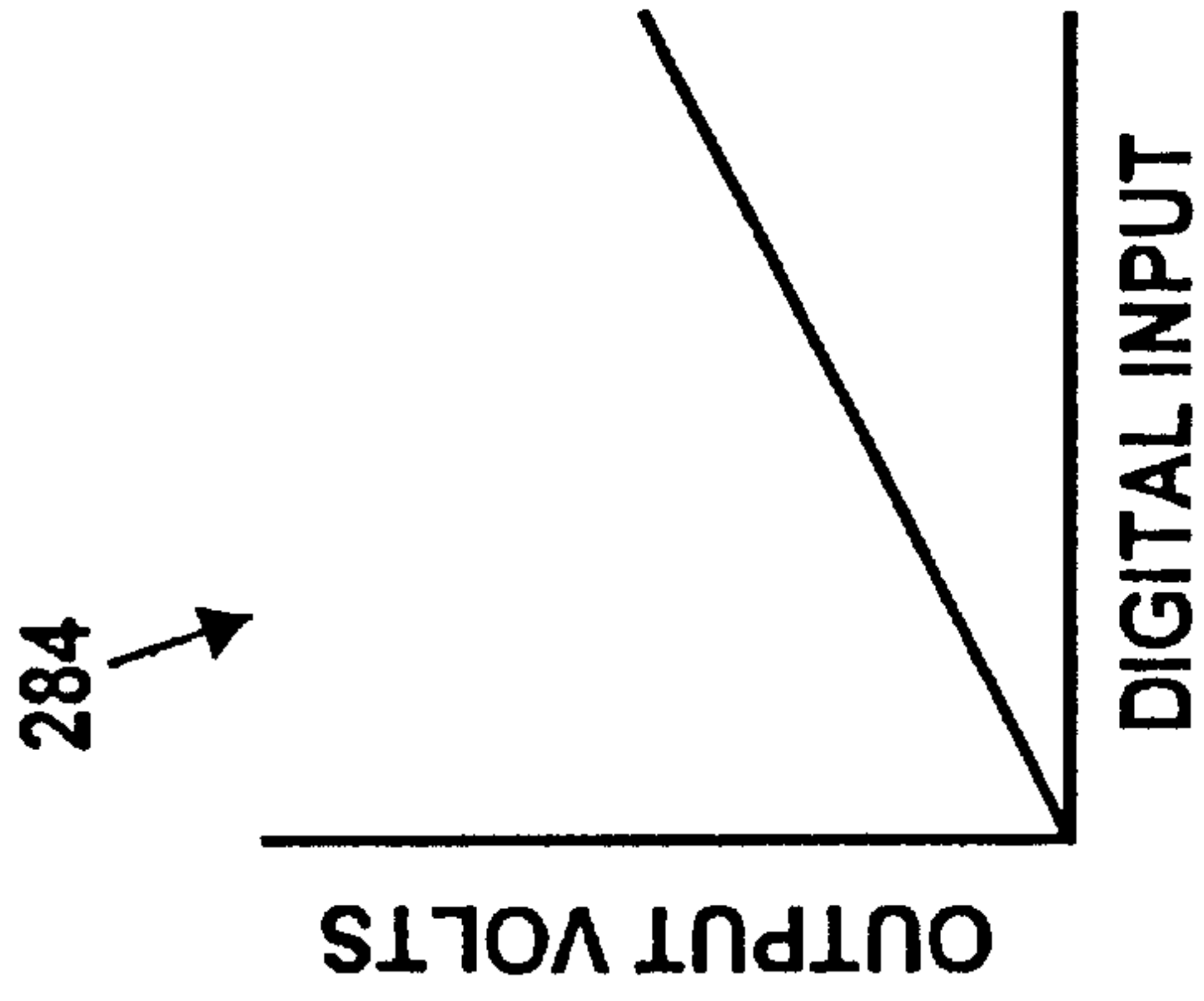


FIG. 14

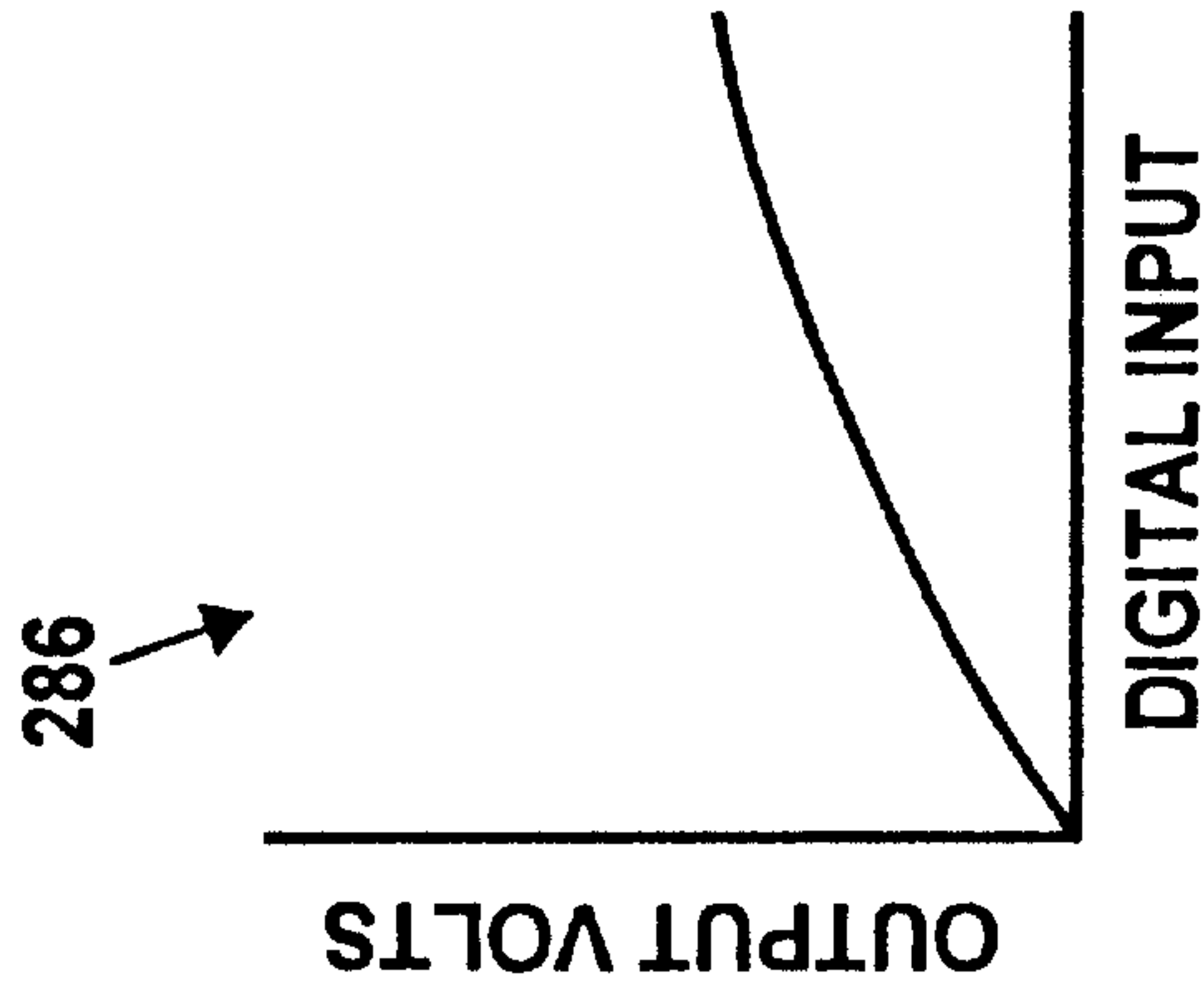


FIG. 15

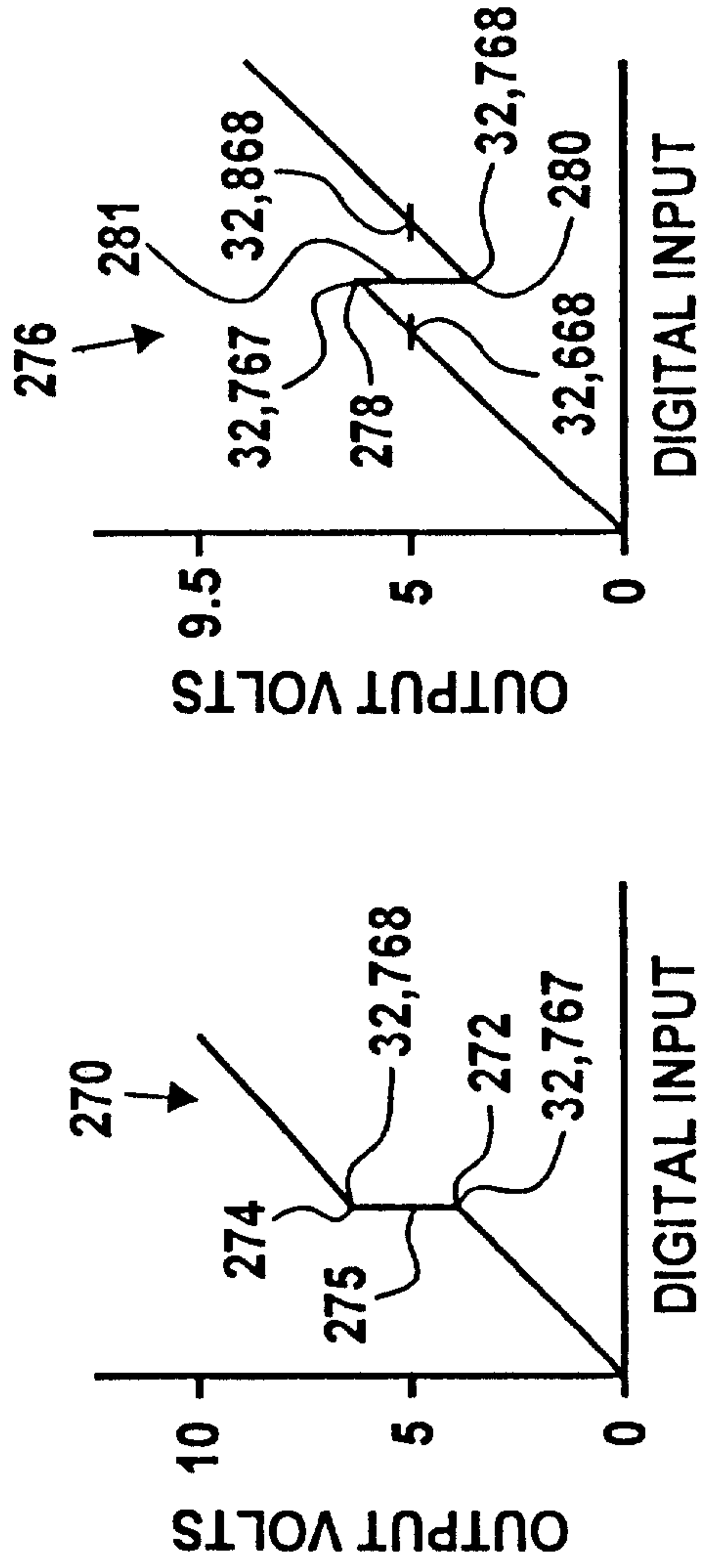


FIG. 12A

FIG. 12B

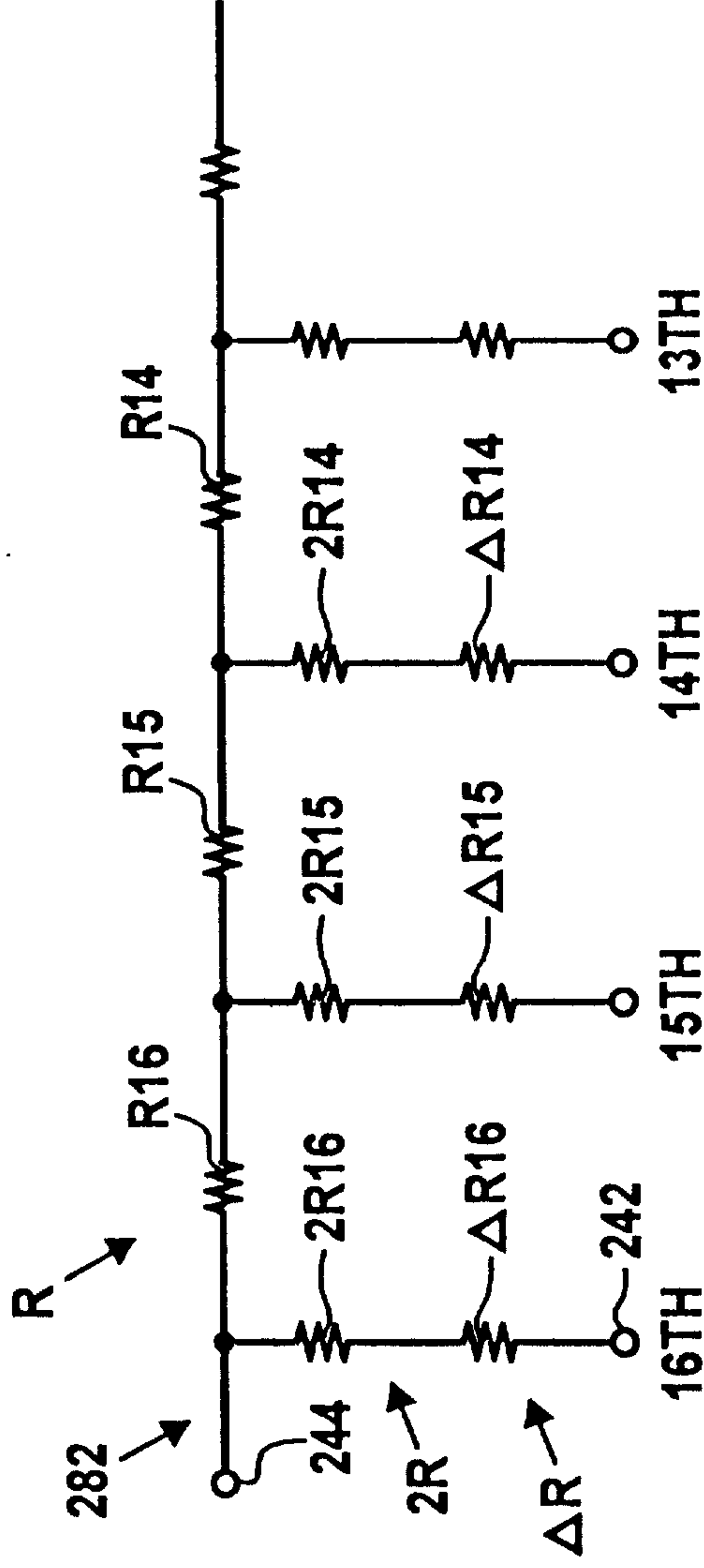


FIG. 13

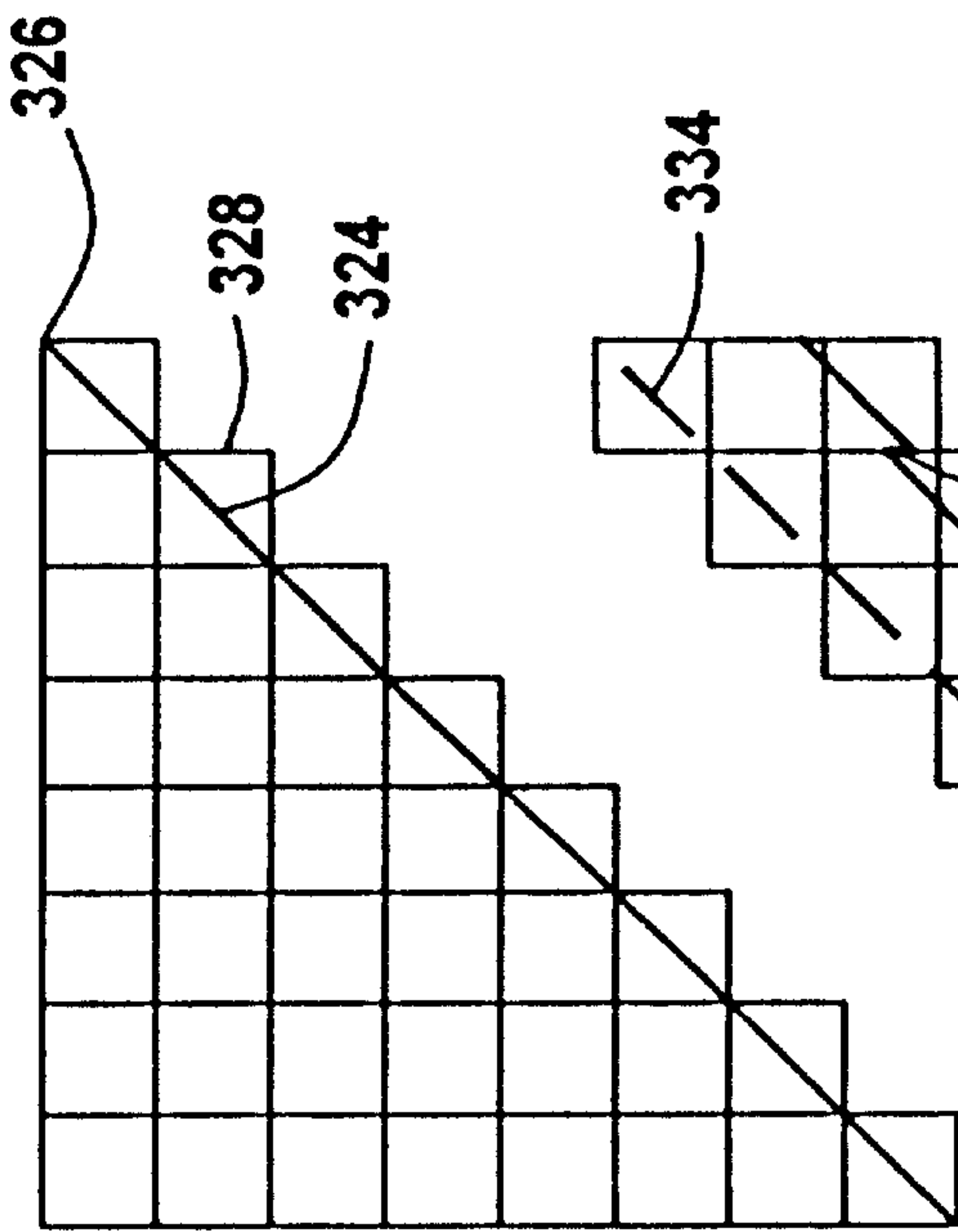


FIG. 18

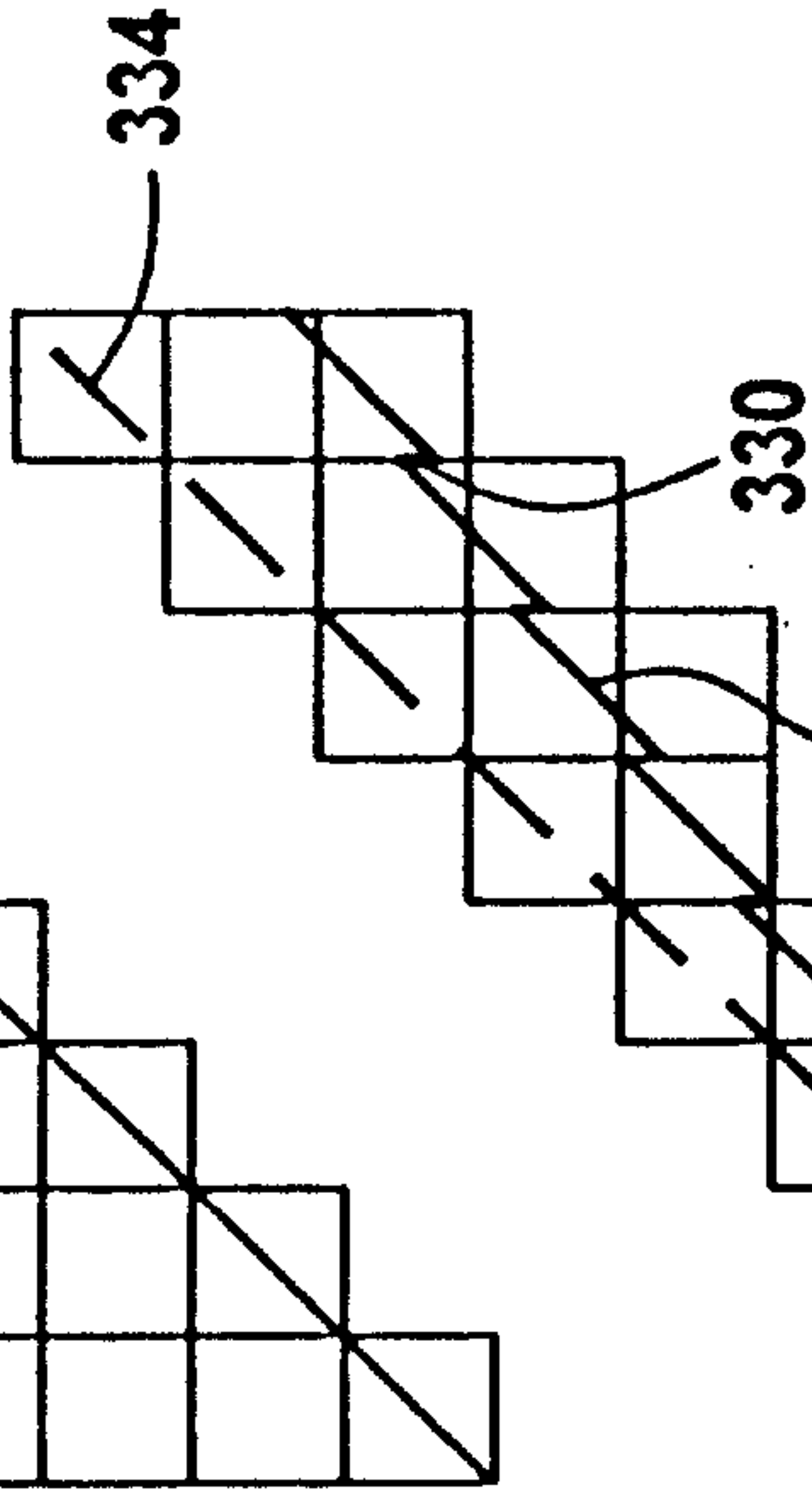


FIG. 19

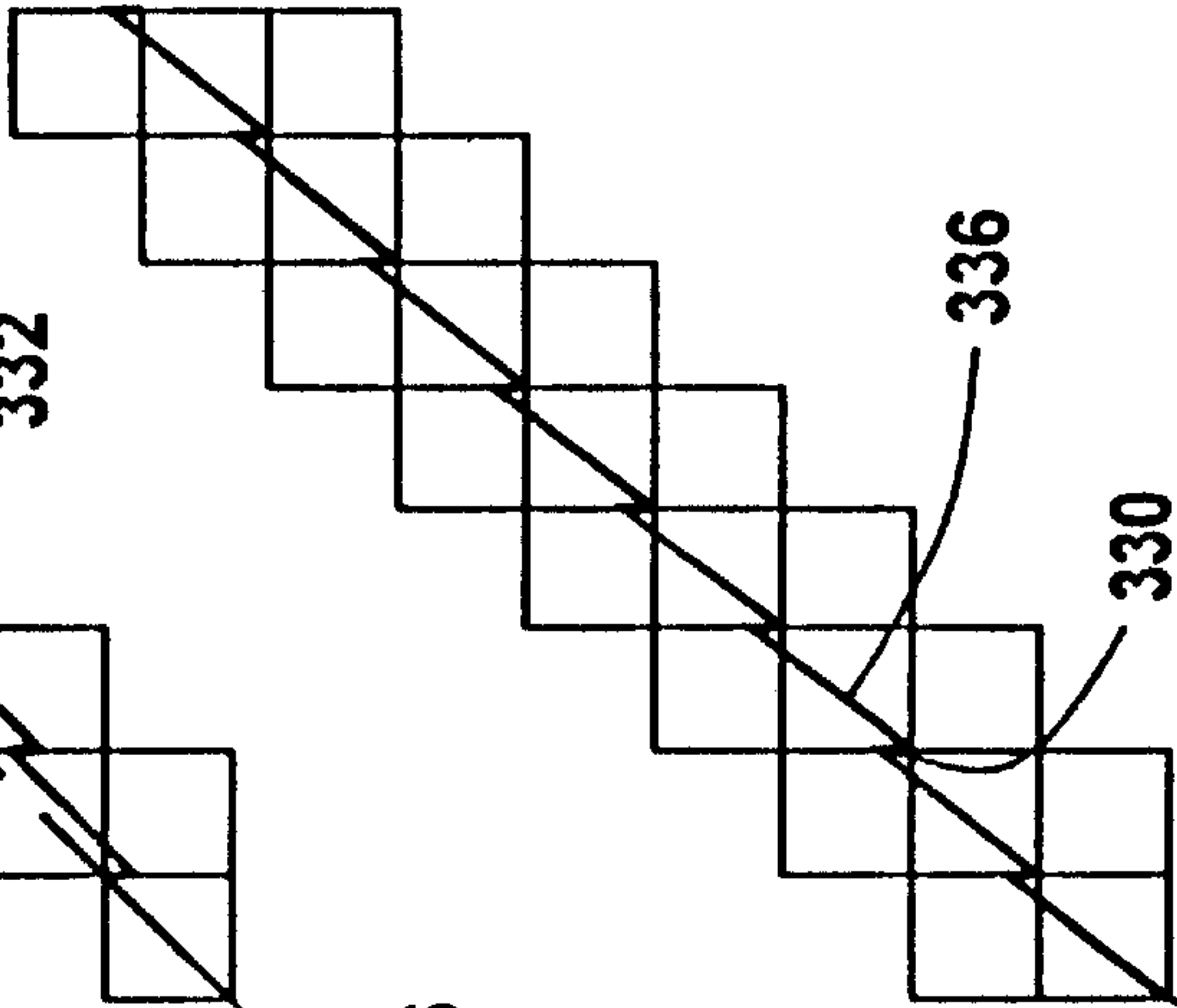


FIG. 20

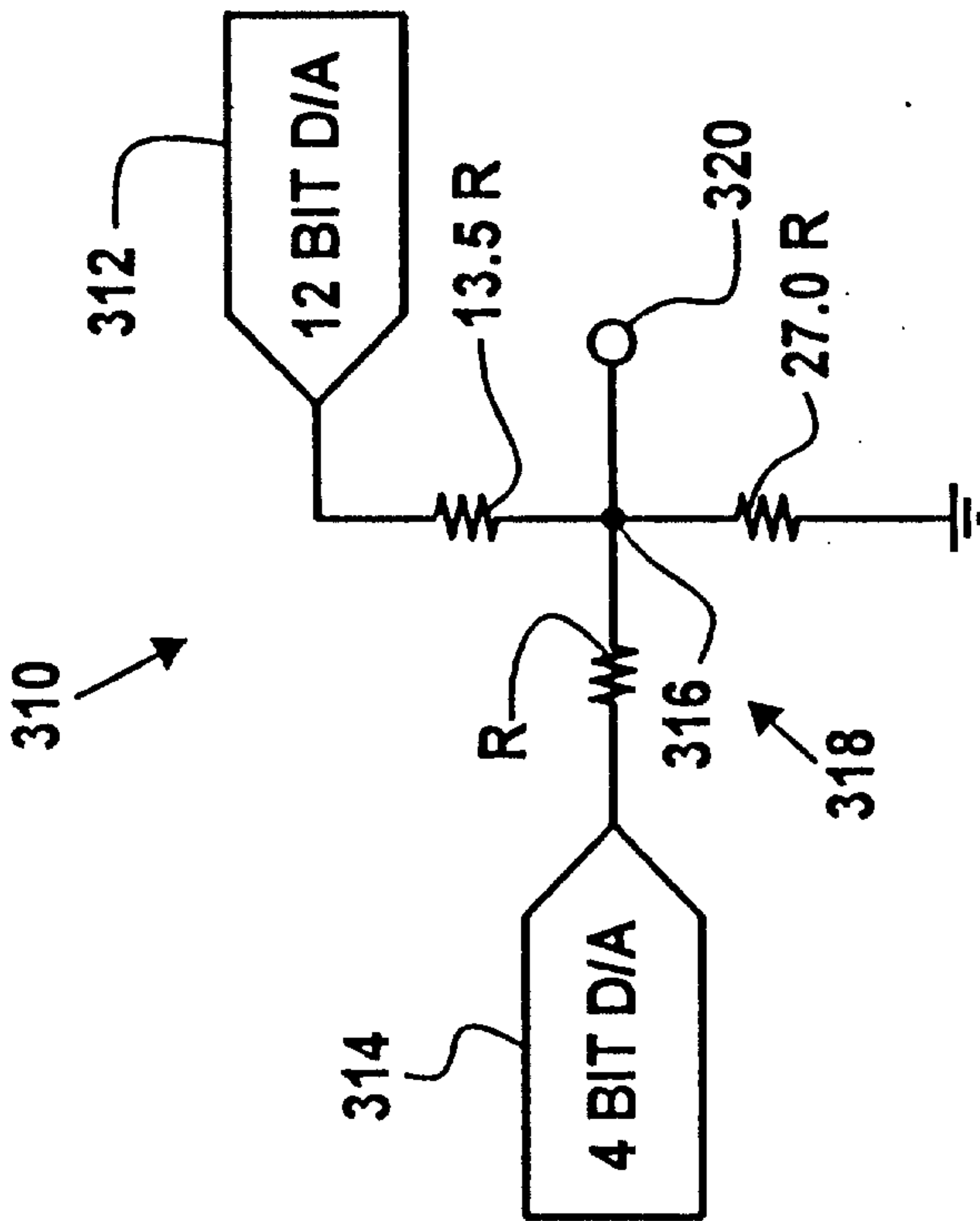


FIG. 17

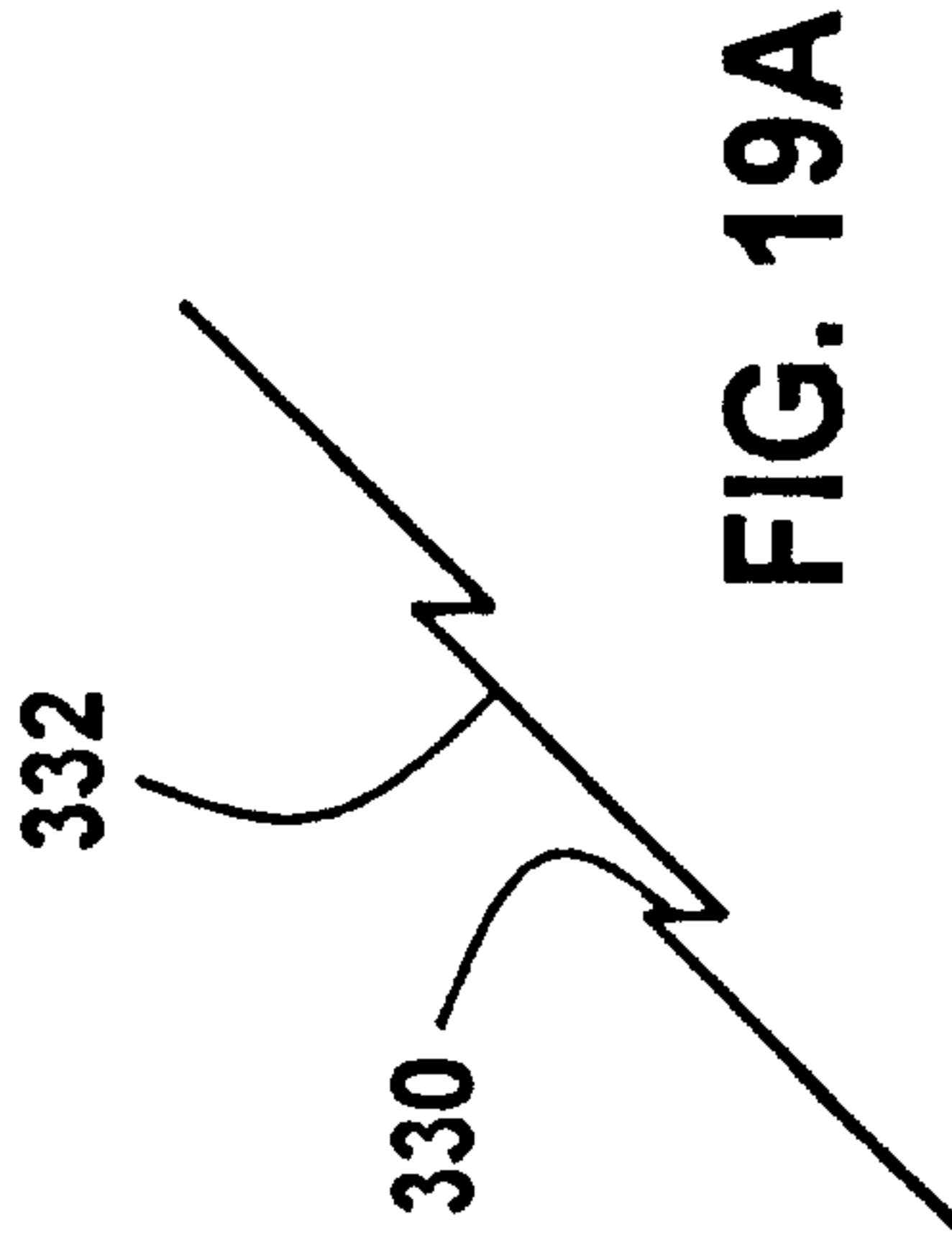


FIG. 19A

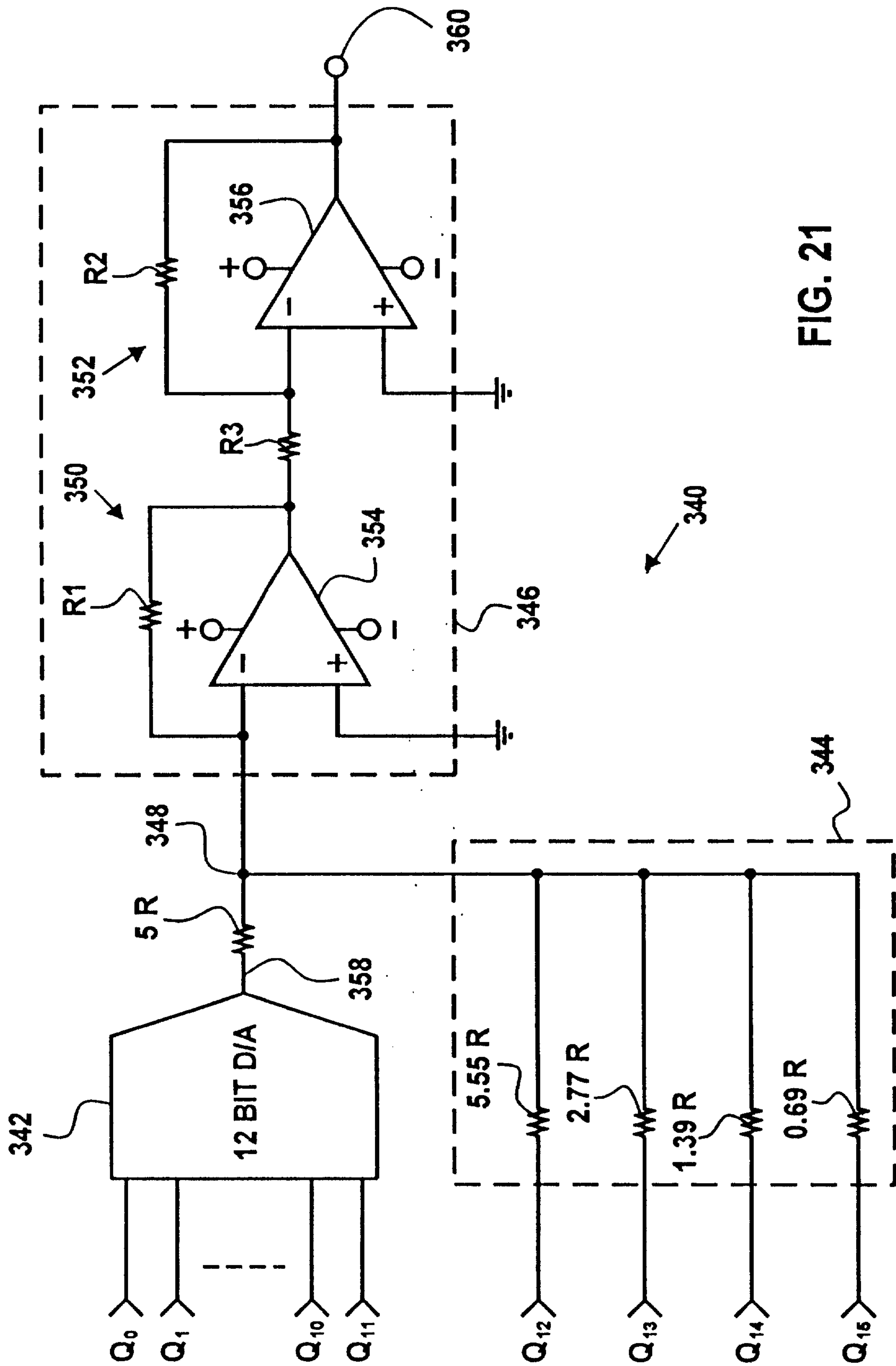


FIG. 21

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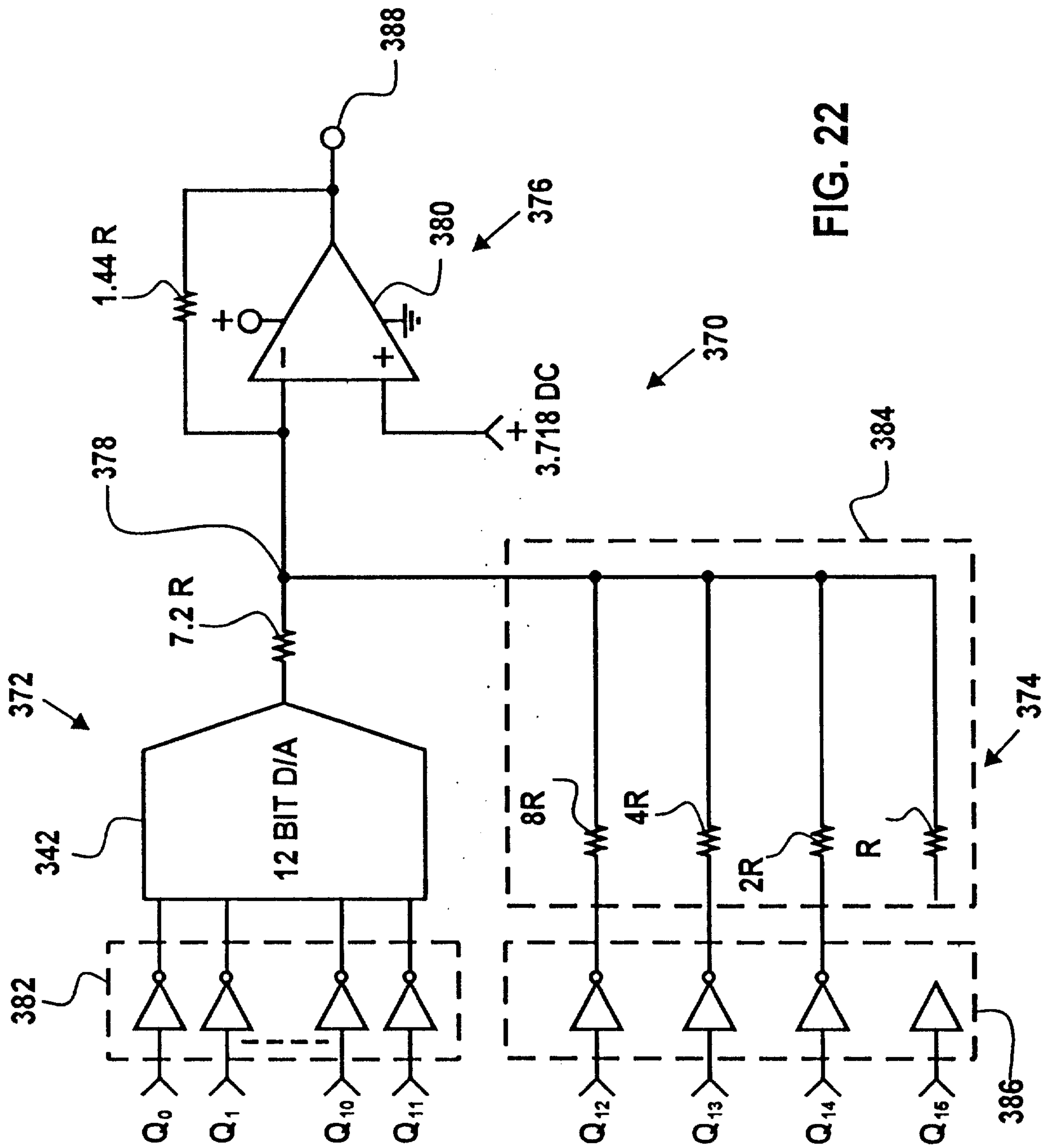


FIG. 22

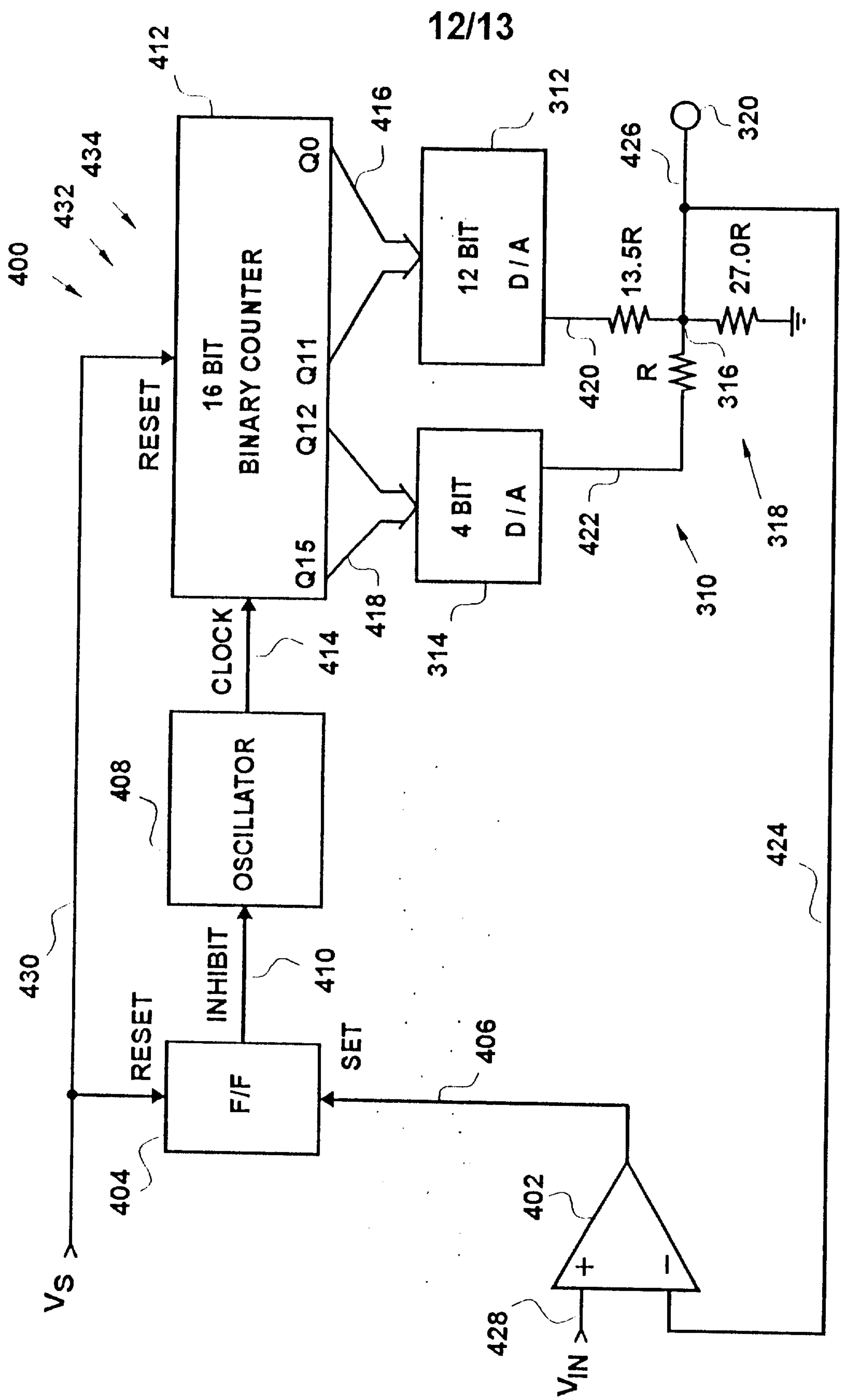


FIG. 23

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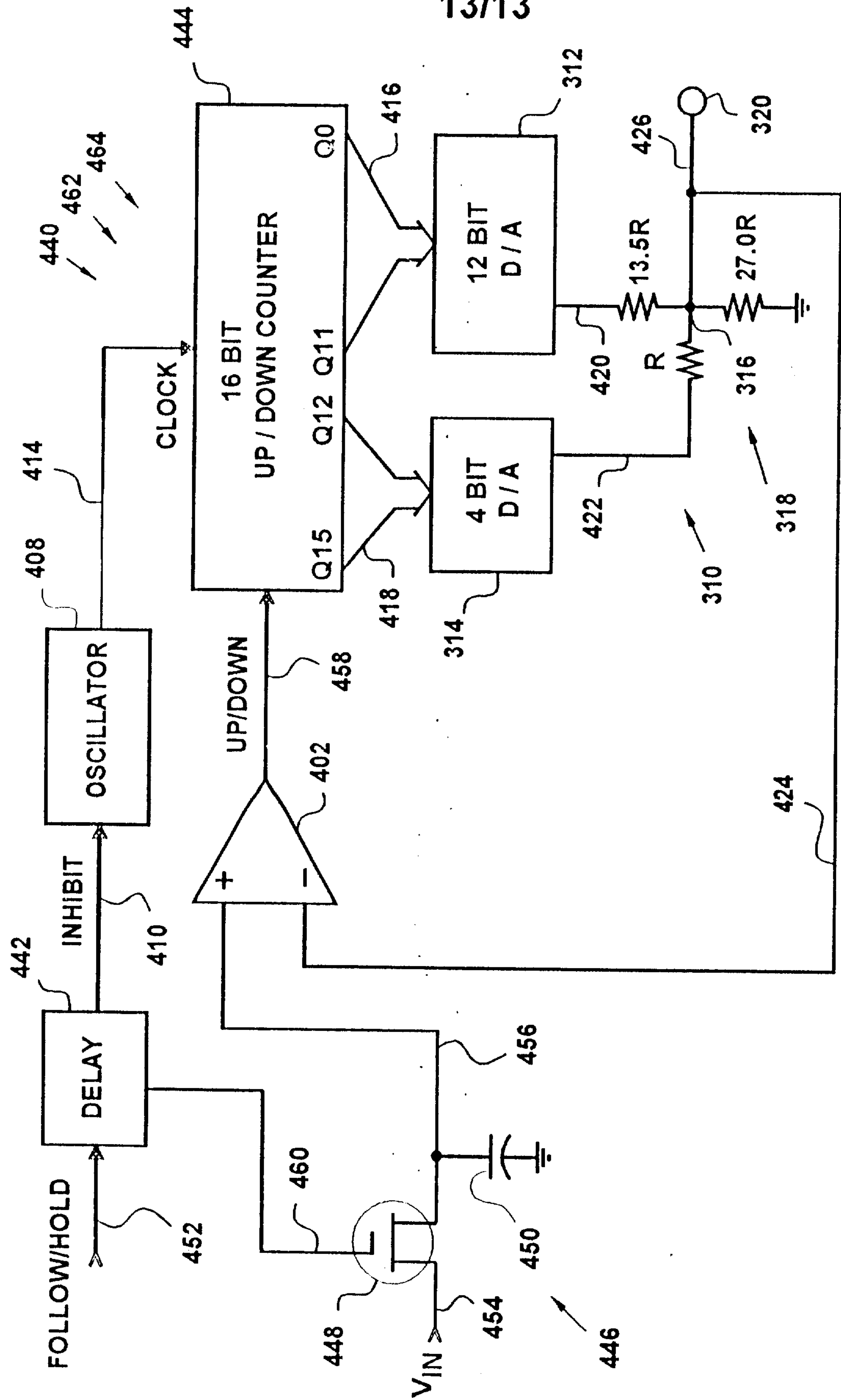


FIG. 24

