APPLICATIONS OF VOLTAGE-CONTROLLED AMPLIFIERS 1846(E-2)

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ABSTRACT

The VCA, with its input, output, and control ports, is described as a generic building block in several designs including: VCO's and VCF's, tracking filters, spectrum analyzers, and distortion analyzers. Methods of remote gain control and console applications including digital control techniques are discussed with a comparison of designs using VCA's and faders.

INTRODUCTION

A Voltage-Controlled-Amplifier (VCA) is a device which accepts an input signal and, based on an applied gain-control voltage, produces an output signal proportional to this input. VCA's are used in audio consoles, noise reduction systems, compressors, expanders, equalizers, and in various other types of signal processing equipment. Unfortunately, VCA's remain a mystery to many would-be users. Even engineers who design with VCA's are often unaware of potential VCA applications beyond the simple replacement of level control fader potentiometers with potentiometer/VCA systems. It is the purpose of this paper to show that the VCA is a building block, much like the operational amplifier or phase-locked-loop, which has a variety of uses.

THE BASIC VCA

There are many kinds of VCA's: voltage-in-voltage-out, current-in-current-out, and permutations thereof. To avoid confusion, this paper will deal with one of the most common types of VCA's: The Blackmer VCA[1]. This is a current-in, current-out unit of the type made by dbx and Valley People (formerly Allison Research). Examples will be shown with dbx VCA's, but the general principles are applicable to other manufacturers' devices and other types of VCAs.

Figure 1 shows a VCA with input, output, and control pins. The input pin acts as a summing junction, maintaining a virtual ground potential. The input signal is the sum of the currents flowing into the VCA input terminal. Since VCA distortion is a function of input current (distortion usually increases with input current), the peak currents into the VCA should be set to ensure the desired distortion performance. The designer should be aware of the tradeoff between distortion and dynamic range. If very low distortion

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[1]Blackmer, David, U.S. Patent #3,714,462, "Multiplier Circuits."

is desired, then input currents must be kept small. However, since the equivalent input noise is fixed, lower input currents imply a lower signal-to-noise ratio. Dynamic range, then, depends on the maximum allowable distortion.

The VCA output signal is a current equal to the product of the input signal and the gain programmed by the gain-control pin. Since VCA distortion is also a function of the output current (again, distortion usually increases with increasing currents), maximum gain may be limited by the maximum distortion allowed.

The output noise is mainly current noise. The output current contains a white noise component which varies with gain. When this noise is referred to the input, the equivalent input noise fortunately varies such that it decreases with increasing gain, and increases with decreasing gain. The slope of the change in equivalent input noise with gain is dependent on the internal biasing method used in the VCA design. Class A VCAs have a relatively constant slope of 1/2, while Class AB VCAs have a slope of 1/4 for positive gains, and 3/4 for negative gains. At large positive gains, the equivalent input noise becomes constant because it is dominated by the VCA internal input amplifier noise. Figure 2 shows these general characteristics graphically. Consult the manufacturer's data sheet for specific characteristics for a particular VCA.

The gain-control port is the reason why a VCA is not just another amplifier. Typically, when 0V (DC) is applied to the control port the VCA output current equals the input current (0dB gain). As the control port voltage is changed, the VCA gain (output current divided by input current) changes. The control constant is usually described as a certain number of decibels-per-volt or volts-per-decibel. This "deci-linear" relationship makes the Blackmer VCA particularly well suited to audio applications, as well as to instrumentation applications where changes in gain are required. The input impedance of the control port often differs from device to device, ranging from 200Ω and up to several kΩ. A low impedance control port offers the flexibility of custom-tailoring the voltage-control constant by adding a resistor in series with the port.

SUPPORT CIRCUITRY

Since the VCA input port is a summing junction (virtual ground) which accepts only input currents, input voltages must be converted to currents via an input resistor or resistors (see Figure 3). The value of the input resistor is a function of the maximum peak signal voltage which will appear across the resistor and the maximum desired input current into the VCA. The peak signal voltage will depend on the previous stages of circuitry, while the maximum input current will depend on the unit's distortion specifications and the desired level of performance. For example, if the peak input voltage is 20V, and the input current must be limited to 1.5mA, then the input resistor value should be 13.3kΩ. When several signals are summed at the VCA input pin (as shown by "other signal voltages" in Figure 2), the maximum input current is the sum of the currents through all the input resistors. Decreasing the value of the input resistor will increase the distortion at a given signal level, but it will also decrease the thermal noise contribution from the resistor (though this is usually insignificant compared to the noise of the VCA).

The input to the VCA should normally be AC coupled. If it is not, DC voltage offsets in the VCA input stage itself, as well as in the stages preceeding the VCA will cause a DC current to flow in the input of the VCA. This DC current is indistinguishable from an input signal current, and will be modulated by the gain command signal along with the desired signal. A sudden gain change will cause the DC current at the output of the VCA to also change suddenly. This transient change is often audible as a low frequency thump. AC coupling the VCA input will avoid these problems.

The output current from the VCA should be applied to the summing junction of an op-amp with a feedback resistor to form a current-to-voltage converter. The summing junction may be used to sum the outputs of several VCA's or combinations of VCA outputs and resistor-fed signal currents. The choice of the proper feedback resistor is more complicated than the choice of input resistor, even in the case of a single VCA, since it is dependent upon the nominal gain of the VCA. For instance, if the designer wishes to have a +6dB of voltage gain at Ec=0V (which is the unity current gain point), then the feedback resistor must be twice the value of the input resistor. If the feedback resistor is too large, though, the op amp will clip with large output currents.

By reducing the value of the feedback resistor, the output noise voltage produced by the VCA output current noise is also reduced.

A small capacitor in parallel with the feedback resistor is necessary for stability. A pole is formed in the op amp feedback loop due to the interaction of the feedback resistor with the VCA output capacitance. The feedback capacitor adds a zero to the feedback loop transfer function which cancels this pole. A value of 33-100pF is usually sufficient, although the RC product of the feedback elements should be examined to ensure that the full bandwidth is not compromised.

VCA's vs. POTENTIOMETERS

Potentiometers ("pots") are often used in console fader packages to control the channel gain. An audio signal voltage is connected across the pot element, and the wiper is connected to the input of an amplifier. The maximum gain is determined by the gain of the amplifier (when the full audio signal voltage is applied to the amplifier input), while the maximum attenuation is determined by the amplifier gain and the voltage divider relationship between the potentiometer end resistance and the overall resistance.

The most common use for a VCA is as an "electronic fader". Instead of passing the audio signal itself through a potentiometer, the signal is passed through a VCA, and a mechanical potentiometer is used to generate the appropriate control voltage for the VCA. A VCA/potentiometer combination offers gain control over more than 100dB range. Often, maximum gain is +20dB, and maximum attenuation is -100dB.

Potentiometers offer many different tapers, depending on the manufacturer. A few examples are: log, reverse log, s-taper, and, of course, linear. Modifying these tapers by resistive loading allows variation on any of the standard tapers. VCA/potentiometer combinations, too, offer much flexibility in choice of tapers. First, the potentiometer itself has its own taper. Second, the DC output voltage of the potentiometer can be processed to produce virtually any taper desired. Further, the Blackmer VCA itself provides a logarithmic gain characteristic. This means that a linear taper potentiometer (which is the easiest to manufacturer) can control the channel gain directly in decibels.

Although pots come in various tapers, many of these tapers are not exactly what would be expected from their name. For example, a "log" pot will often be approximated with a multi-taper element: several linear tapers in one element to make a piecewise linear approximation of the log characteristic. The maximum attenuation end of the pot is usually where the taper is least accurate, since a conductive compound is often painted on the element to reduce hopoff, thereby insuring full attenuation. Unfortunately, this also insures that, towards the end of the wiper travel, the taper will be far from logarithmic. Nonlinear pot tapers are often inconsistent from unit-to-unit, as well. This means that two ganged pots will rarely track each other accurately.

Linear potentiometers, on the other hand, can be made easily, accurately, and inexpensively. VCA's offer exponential gain control with a linear control voltage. Therefore, a VCA controlled by a linear pot can be used to provide a fader control which is linear in decibels. The "piecewise-log" pots used in console faders attempt to provide this control taper. Additionally, the VCA control characteristic is consistent between units, so many VCA's may be "ganged" together and track each other quite accurately.

Potentiometers offer very good temperature performance. If the top of the pot is connected directly to a low-impedance source and the wiper is not loaded excessively, then the pot will not change its voltage dividing ratio with temperature changes. If a series resistor feeds the top of the pot, then the situation may change entirely. When the series resistor's temperature coefficient is different from that of the pot, the voltage applied to the pot will change with changes in temperature. Further, if the taper of the pot is optimized by loading the wiper with a resistor with temperature characteristics which differ from those of the pot, again, the overall gain will be temperature-sensitive.

Blackmer VCA's themselves are inherently temperature-sensitive. The control port gain constant will typically vary with temperature 0.33%/degree Celsius. This means that at Ec = 0V, there is no gain variation with temperature, but as the gain is increased or decreased from this point the gain change with temperature becomes more and more severe. The actual impact of this effect will depend on the particular application and whether the designer wishes to include temperature compensation circuitry in the equipment (more on that later).

Potentiometers have excellent frequency characteristics; rarely are pots the limiting factor in the frequency response of a fader. (Although capacitive pick-up can be a problem in the middle of a pot's range - where the wiper sees the highest source impedance.) Similarly, only a few "golden ears" can hear the distortion caused by pots. The noise, too, is only the thermal noise of the resistance element, and can be arbitrarily low. The only pot noise which is a major problem is adjustment noise. This is the noise caused when the wiper contact skips over dust or dirt on the element, momentarily losing the signal. Old, worn pots may have impressions on the element where the wiper has remained for long periods of time. When the wiper is brought past this spot, there can be a momentary loss of signal. These mechanical problems lead to limitations on the useful lifetime of a potentiometer.

The frequency characteristics of VCA's are quite a different story. Even with attenuation, the VCA will roll off sooner than would a pot - somewhat in the same manner as the amplifier which follows the pot. With gain, however, the bandwidth diminishes far enough that - at very high gains - the frequency response can roll off within the audio band. Distortion, also, is often more readily measurable in a VCA, although recent VCA designs have challenged even the "golden ears" to hear distortion effects. The steady-state noise from a VCA is typically worse than that for a potentiometer. However, VCA noise changes with gain as shown in Figure 2, while the thermal noise of a potentiometer is worse at 6dB below full gain and drops off at either end. VCA adjustment noise, however, is not a problem. By processing the DC control voltage generated by the pot which controls the VCA, any adjustment noise can be filtered out. This filtering may be designed, if desired, to slow the speed of gain changes to an arbitrary rate consistent with the application: automatic faders, for instance.

GAIN-CONTROL APPLICATIONS

Figure 4 shows an example of a single potentiometer controlling a single VCA. The bipolar supply is applied across the pot, and the wiper voltage is divided down to ±1V, at the VCA control port. Since this VCA's gain control constant is -50mV/dB, the resulting gain range will be ±20dB. By adding an offset resistor, as in Figure 5, the control voltage can range from 0V to +2V, corresponding to a gain control range of 0dB to -40dB. This passive control circuit is the simplest form of gain control with a VCA. The 250µf, 6V, electrolytic capacitor filters pot adjustment noise and power supply noise, and reduces stray signal pickup at the control port.

A single pot can control a number of VCA's. To accomplish this, the control ports of several VCA's may be tied together in a circuit much like that of Figure 4. However, multiple control port impedances, when driven in parallel, often require that the control voltage come from an active buffer, as in Figure 6. (this is especially important when the control port input impedance is low to begin with.)

The circuit of Figure 6 has the advantage that the control port always sees a low-impedance voltage source, reducing distortion and stray pickup.

However, there is a tradeoff: noise. The noise of the active control circuits will modulate the gain of the VCA - a classic example of noise modulation. Often this noise will be negligible: 5μV of noise on a 50mV/dB control line will contribute noise more than 98dB below the input signal level. However, a noisy op amp used in a high gain configuration as a control voltage summer (see the next paragraph) may cause more noise modulation than desired.

Figure 7 shows the gain offset of Figure 5 applied to the circuit of Figure 6.

A number of potentiometers can control a single VCA. Again, an active control circuit is used. An op-amp summer adds gain-control voltages from a number of pots with the summed voltage controling the VCA, as in Figure 8. The gain control range may be increased by increasing the feedback resistor alone, and range offset could be accomplished by connecting a resistor from the appropriate supply to the summing node as was shown in Figure 7. Each pot may be located at some distance from the VCA. Furthermore, one of the pots could be used to control several VCAs simultaneously, as in a console grouper.

Occasionally, the need for non-linear control voltage processing arises. For instance, one may limit the maximum gain or cut (Figure 9) with a simple clipper followed by an offsetting buffer. The clipper determines where the pot(s) control action ends, while the buffer offset and its gain sets the maximum value of gain or cut.

Sometimes a single taper is not appropriate. Figure 10 illustrates a method of changing the control taper above an arbitrary point. Above unity gain, the pot controls gain at -2V/dB while, below unity gain, the control characteristic is -1V/dB.

As mentioned previously, VCA's are temperature-sensitive. For applications where the VCA temperature will vary widely, temperature compensation may be in order. Although unity current gain occurs at Ec = 0V, regardless of temperature, the gain-control constant has a temperature dependence of 0.33%/degree Celcius. The circuit of Figure 11 uses a temperature dependent resistor to compensate the VCA control port temperature sensitivity.

AUTOMATIC GAIN CONTROL

Up to this point, all gain control has been through the use of potentiometers. Of course, there is no reason why potentiometers must be used at all. They simply provide a method of programming a voltage for the VCA control port. A Digital-to-Analog (D/A) converter could also be used to provide a control voltage, with repeatable voltage settings under computer control. This is the basis of automation systems which use VCA's. With voltages generated by a D/A, some additional circuitry is needed, however. Since a D/A can change output voltages very quickly (possibly with glitches along the way), some slew limiting and filtering should be used to protect against control voltage feedthrough. Control feedthrough occurs when high frequency energy presented to the control port is capacitively coupled to the output, or when offset changes versus gain, thereby feeding a component of the control voltage to the VCA output. This problem can be minimized by making instantaneous gain changes with muting relays, for instance, or by avoiding quick gain changes altogether. An example of the latter approach in a D/A-controlled VCA is given in Figure 12.

Signals can also be used to control the gain of a VCA; this is the principle behind compressors and expanders. The block diagrams in Figure 13 show how a signal, applied to a level detector, can change the gain of a VCA to compress signals above a threshold.

FREQUENCY-CONTROL APPLICATIONS

A simple method for generating a shelving equalizer is by splitting the audio band in two, giving each band a different gain, and recombining bands. Figure 14 shows the band-splitting network with a VCA in one path and resulting response curves.

VCA's may be used in the current-gain mode to vary the apparent value of a resistor. In Figure 15, a voltage-controlled integrator is shown. This is very much like the original VCA configuration in Figure 3, but the component values have changed significantly. A large-value gain limiting resistor (R_D) must be used for DC stability. The response of this integrator is a 20dB/decade rolloff which is frequency or amplitude controllable, depending on one's point of view.

An extension of the integrator is the single-pole filter shown in Figure 16. This is actually a state-variable filter and offers both high-pass and low-pass outputs. The first stage compares the input signal with the low-pass output: the difference is the high-pass output. Since there is DC feedback from the integrator output back to its input, there is no need for the stabilizing resistor of Figure 15; the VCA must not be AC-coupled. Analyzing the filter yields the transfer functions (where "g" is the gain of the VCA), and response curves also shown in Figure 16. Interestingly, the gain at either output is ultimately unity, independent of VCA gain; the VCA controls the -3dB frequencies of the two filter outputs.

What, then, is a "dB" of frequency? The VCA simply multiplies current by a number of dB per mV of applied control voltage; it is not a frequency-dependent device. By changing the apparent value of the integrator resistor, though, the RC product of the integrator can be varied, resulting in frequency-control. A "dB" in frequency, then is $20 \cdot \text{Log}(F_2/F_1)$. This is an appropriate definition of a decibel applied to frequency ratios rather than voltage ratios. A VCA with a 20dB/Volt gain control constant would shift the -3dB point by a decade in frequency with a 1V change in control voltage.

A second-order state-variable voltage-controlled filter can be made with two VCAs as shown in Figure 17. Three outputs are available: high-pass, band-pass, and low-pass. Frequency control is proportional to the square root of of the product of the gains of the two VCAs. The value of Q is given by R_2/R_1, when the VCA gains are the same. This topology offers an interesting control feature: W can be controlled independent of Q by tracking the gains of the VCAs together, while Q can be adjusted independent of W by tracking the VCA gains in reciprocal of one another.

A general problem with this topology is that of 'Q-enhancement'. At high frequencies and higher values of Q, excessive phase shifts from the op amps and the VCAs cause Q to be slightly larger than the design value. Adding a light phase lead by bridging the VCA input resistors (labeled 'R') by small capacitors can help this situation.

If, in the circuit of Figure 17, R_2 were increased to infinite resistance, Q will go to infinity. A filter with infinite Q will continue to ring, theoretically, forever. To produce a continuous, pure sine wave, it is necessary to balance the Q of such a filter at precisely infinity. The circuit of Figure 18 adds a VCA (VCA_3) to accomplish this effect. When the gain of VCA_3 is unity (E_C = 0V), the signal current inversion in VCA_3 will cause the current contributed to the first op amp summing junctions from VCA_3's output to exactly cancel the current contributed by R_2. This is equivalent to infinitely increasing the value of R_2 in Figure 17.

A log responding level detector, fed from the signal output, applies 0VDC to the control port of VCA_3 when the output signal reaches the desired level. When the signal output level is too low, the gain of VCA_3 is increased, increasing the Q beyond infinity, insuring that oscillation will start. As the output signal builds, the gain of VCA_3 is decreased, reducing the Q and the signal level. The system therefore tends to settle into a stable oscillation.

The frequency of oscillation, as in the VCF, is controlled by the gains of VCA, and VCA_2. A 20 dB change in gain changes the frequency by one decade.

Given a variety of VCFs and VCOs, quite an assortment of applications spring to mind. A VCO tied to a VCF notch filter constitutes the main part of a frequency-sweepable distortion analyzer. With the notch filter always cancelling the fundamental frequency produced by the VCO, a meter which reads in dB can give a direct indication of THD. If the notch filter is replaced with a sharp band-pass filter with its VCAs slightly offset in gain from those of the VCO, a time-delay spectrometer is possible. The VCO produces a frequency which is fed, perhaps, to a loudspeaker, while the VCF takes its input from a microphone some fixed distance away from the speaker. As the control voltage is swept, the VCO frequency increases and the VCF begins to process the microphone signal. Based on the propagation delay from speaker to microphone, the frequency sweep rate, and the frequency offset between the VCF and VCO, a picture of amplitude versus time and frequency can be painted.

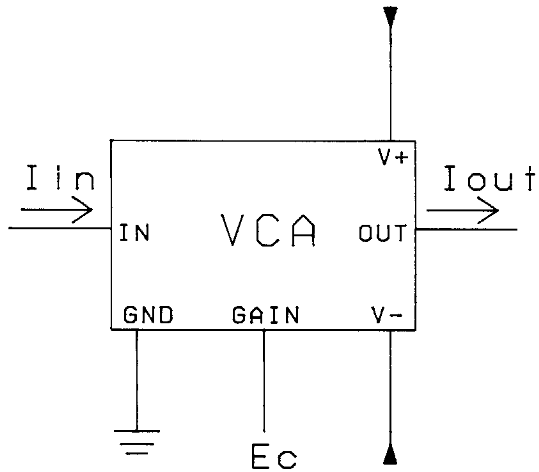
SUMMARY AND CONCLUSION

VCA circuits are not particularly complicated. Often, a potentiometer could perform the same function as a VCA, yet the VCA offers electronic control rather than mechanical control over a particular circuit parameter. Remote gain-control applications are often more suited to VCAs than pots because many signals cannot be practically brought to the pot location.

VCAs offer great flexibility in console design where single or multiple faders are used to control single or multiple signal channels. Signals need not deteriorate passing through many fader channels - rather, control voltages may be passed through many channels and summed to act on a single VCA. In automation systems, VCAs can be used with D/A converters to provide computer-controlled gain control.

Frequency control is also possible with VCA's. Voltage-controlled filters in a variety of topologies are possible. Classic circuits such as state-variable filters are easily voltage-controllable using VCAs. Oscillators with VCAs can be logarithmically swept in frequency with an external control voltage. VCFs and VCOs can be made to track very accurately for specialized applications.

Clearly, there are myriad uses for VCA's in audio applications, alone. With a variety of VCA's available from several manufacturers, a particular VCA may be chosen for each situation. Data sheets for individual units can be used to custom-tailor interface circuitry. Ultimately, as VCA designs become more commonplace, innovative circuits will become widely used and the VCA will earn its place in many engineers' bags-of-tricks.



$$I_{out} = -I_{in}(GAIN)$$

$$GAIN = 10^{\left(\frac{-E_c}{1V}\right)}$$

CONTROL CONSTANT=-20dB/VOLT

FIGURE 1. THE BASIC VCA

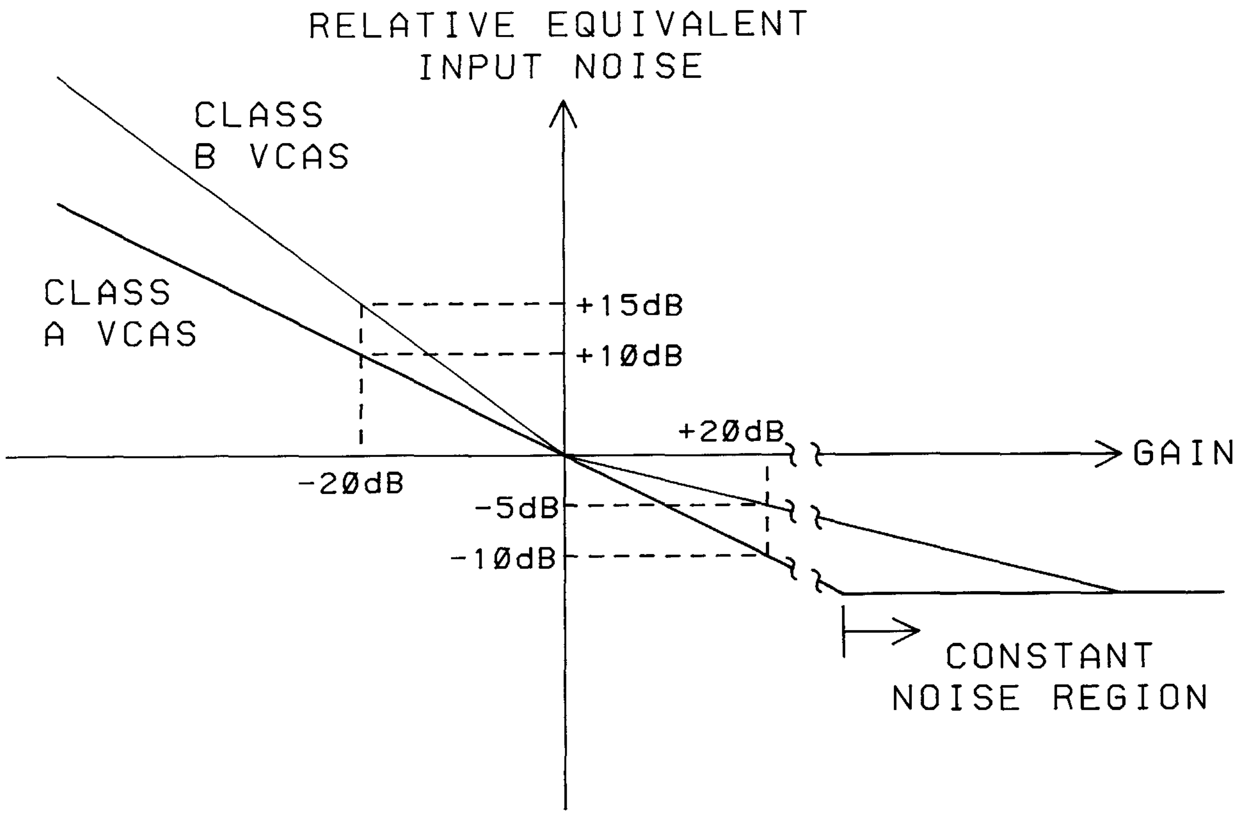


FIGURE 2. EQUIVALENT INPUT NOISE VS.
GAIN IN A BLACKMER VCA

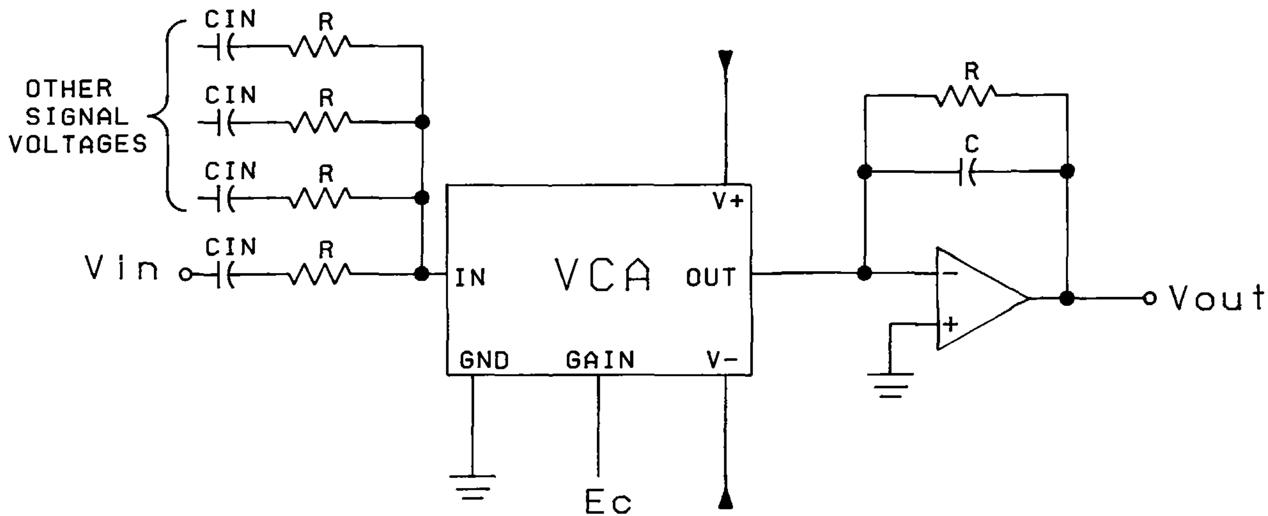


FIGURE 3. AN IN-CIRCUIT VCA

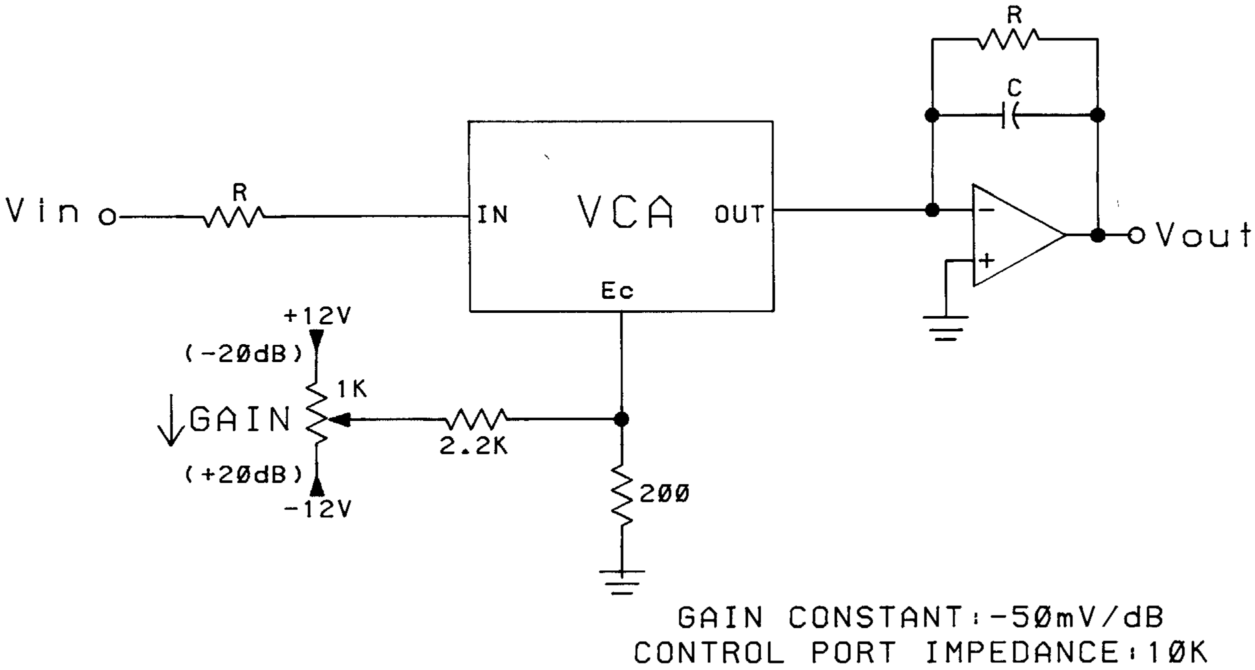


FIGURE 4. SINGLE-POT, SINGLE-VCA GAIN CONTROL

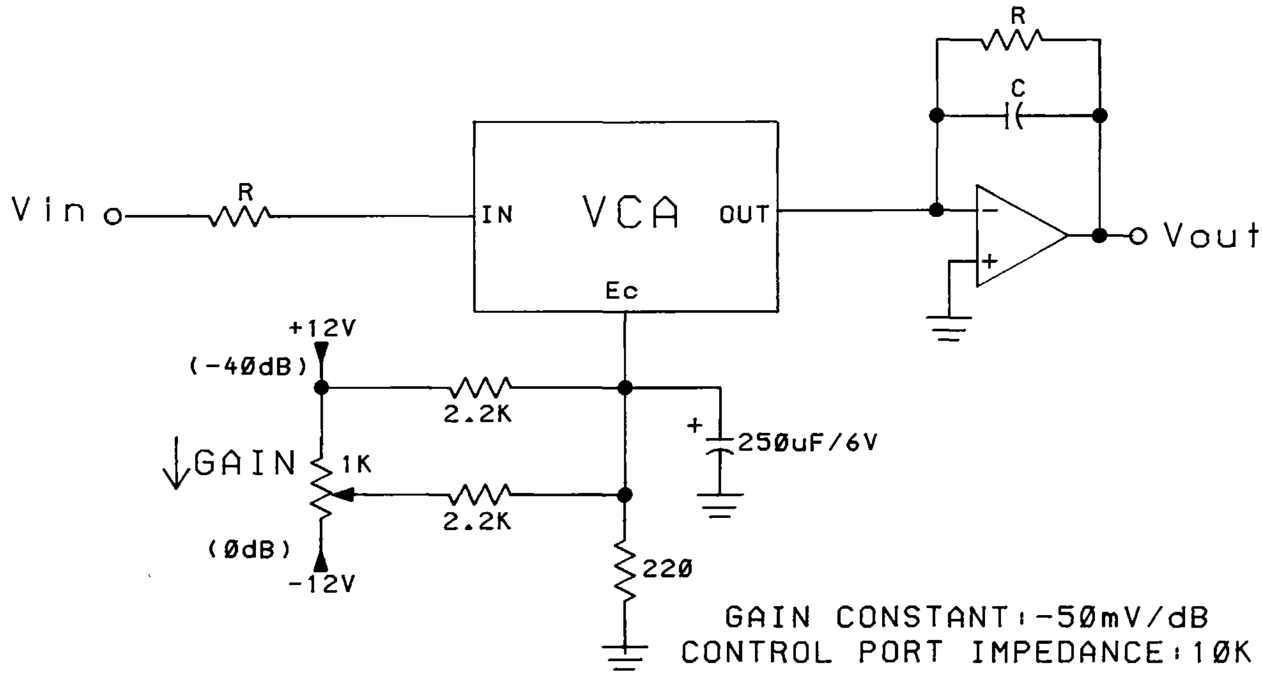


FIGURE 5. SINGLE-POT, SINGLE-VCA GAIN CONTROL WITH GAIN OFFSET

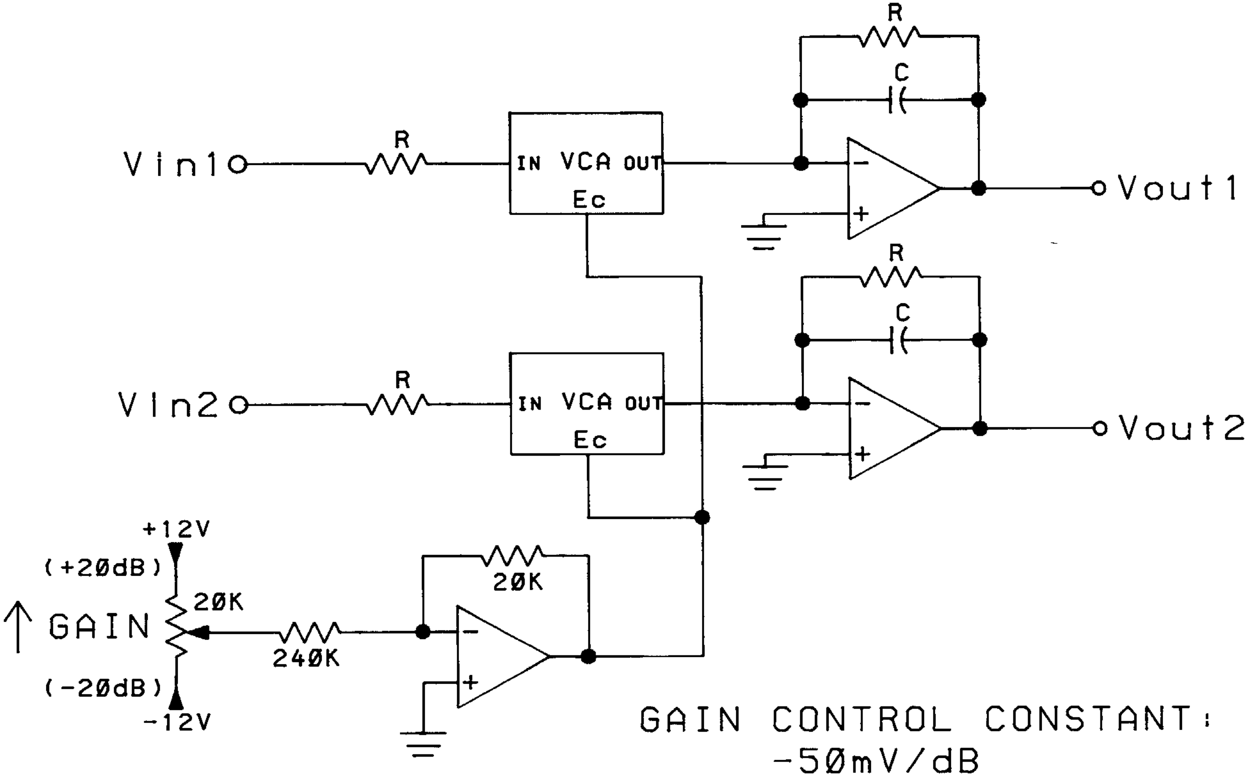


FIGURE 6. SINGLE-POT, MULTIPLE-VCA GAIN CONTROL

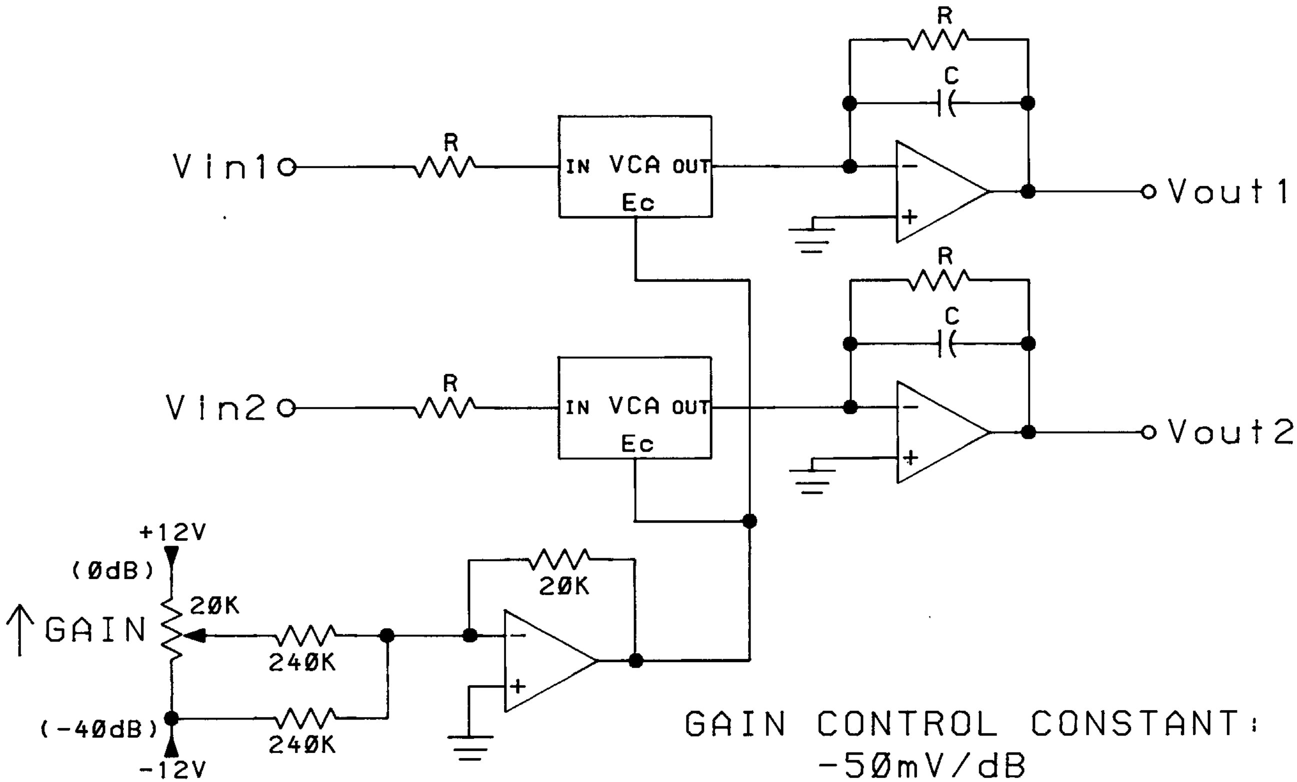


FIGURE 7. SINGLE-POT, MULTIPLE-VCA GAIN CONTROL WITH GAIN OFFSET

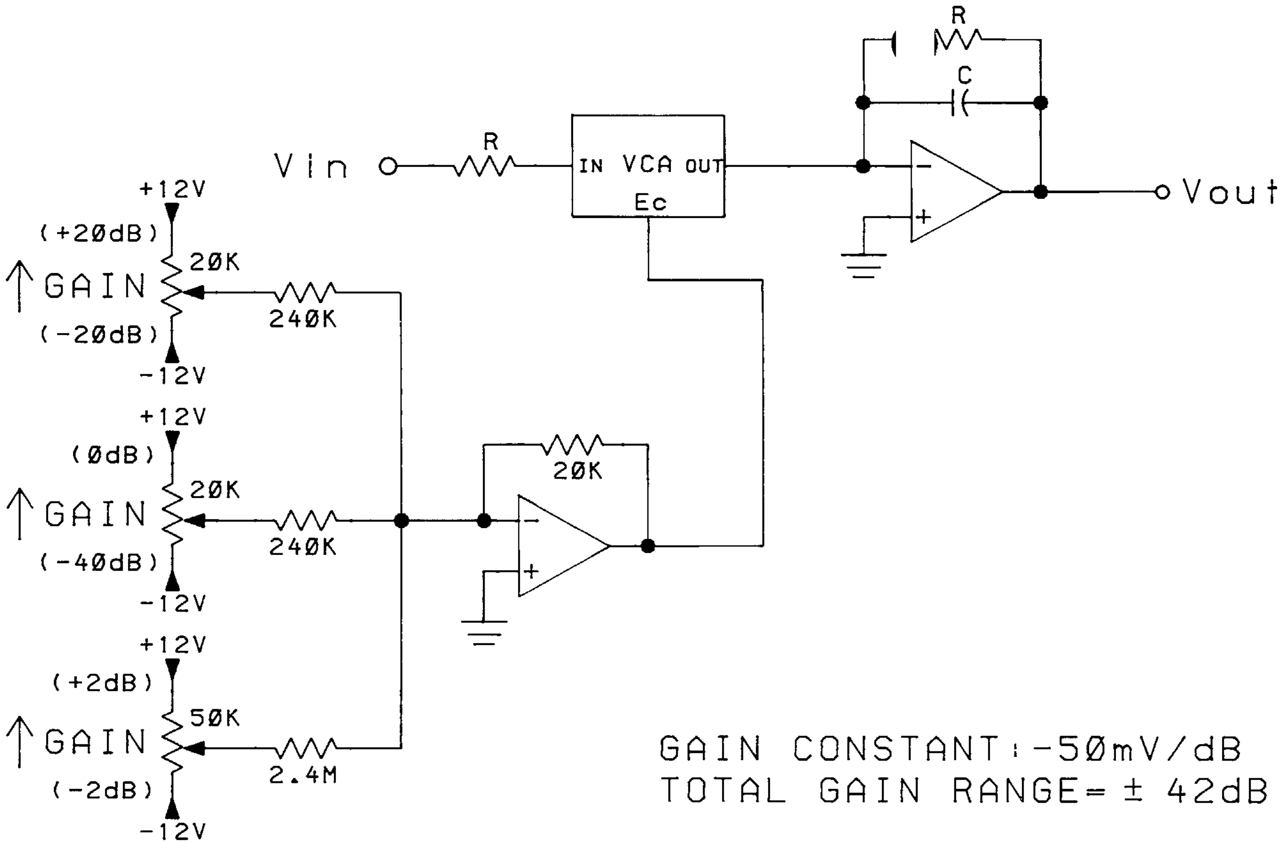


FIGURE 8. MULTIPLE-POT, SINGLE-VCA GAIN CONTROL

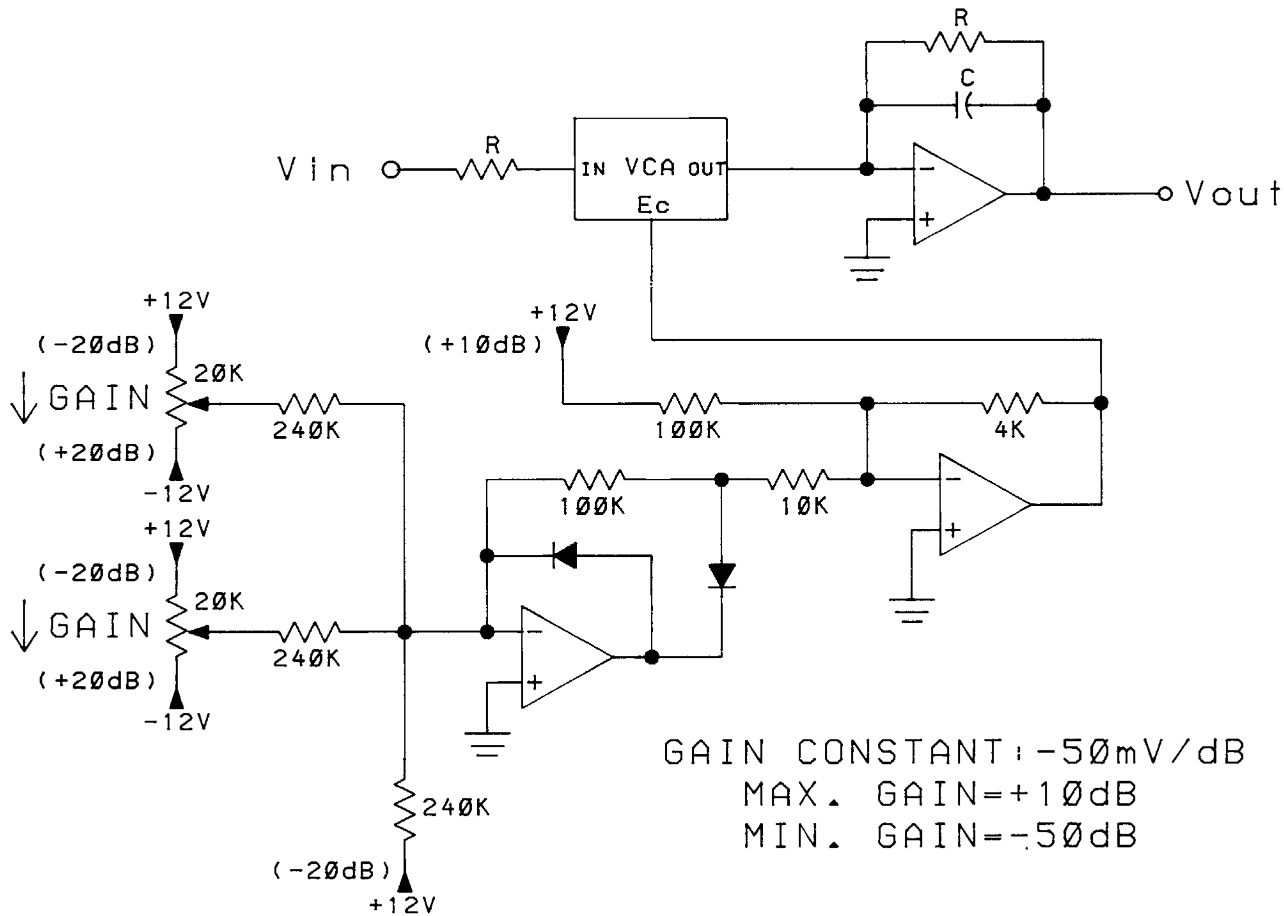


FIGURE 9. LIMITING MAXIMUM VCA GAIN

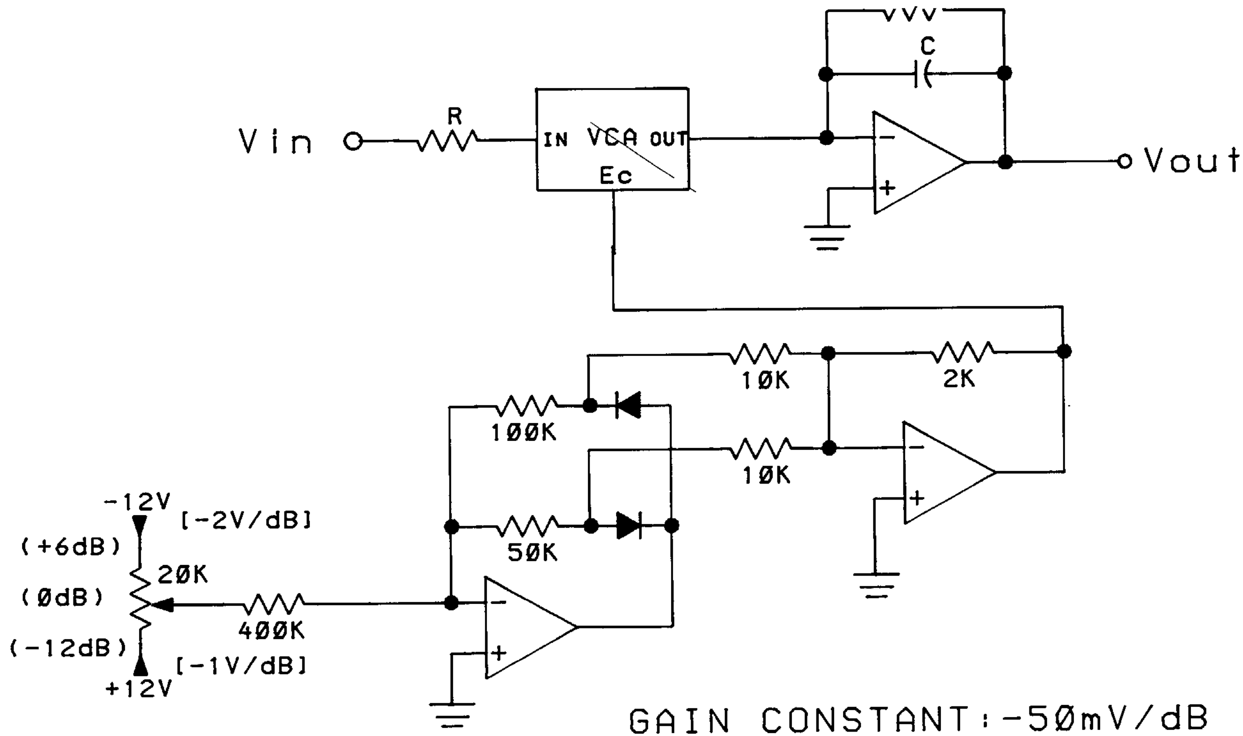


FIGURE 10. TWO-TAPER GAIN CONTROL

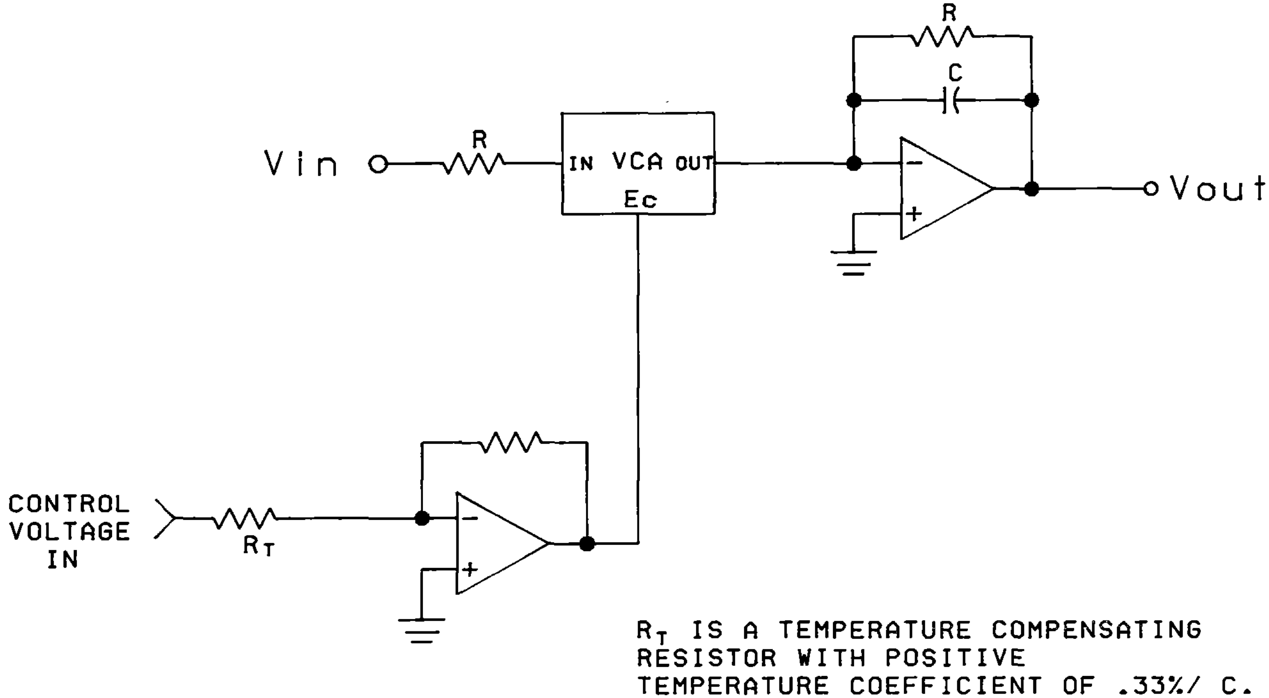


FIGURE 11. GAIN PORT TEMPERATURE COMPENSATION

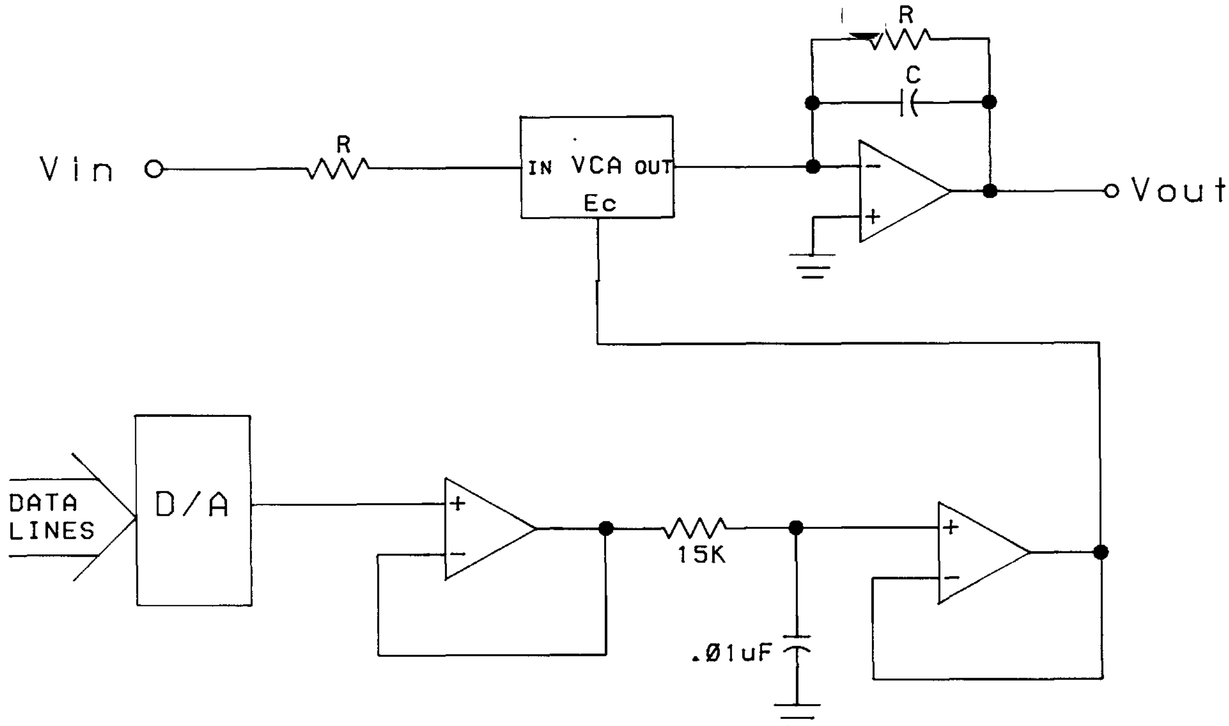


FIGURE 12. D/A-CONTROLLED GAIN

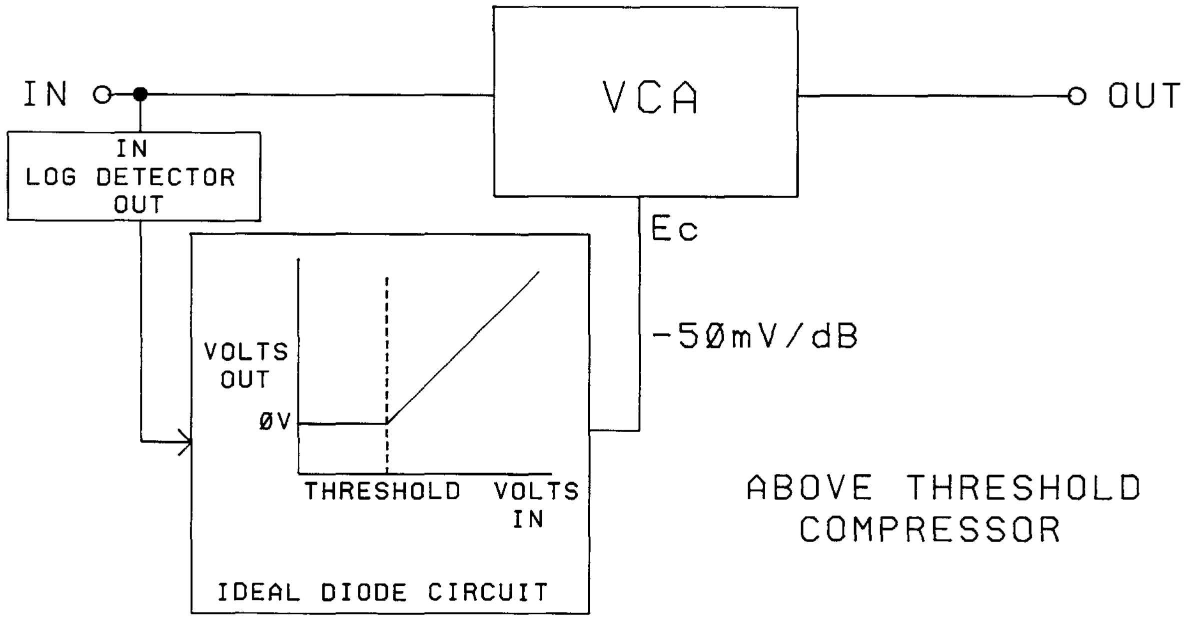


FIGURE 13. SIGNAL-CONTROLLED GAIN

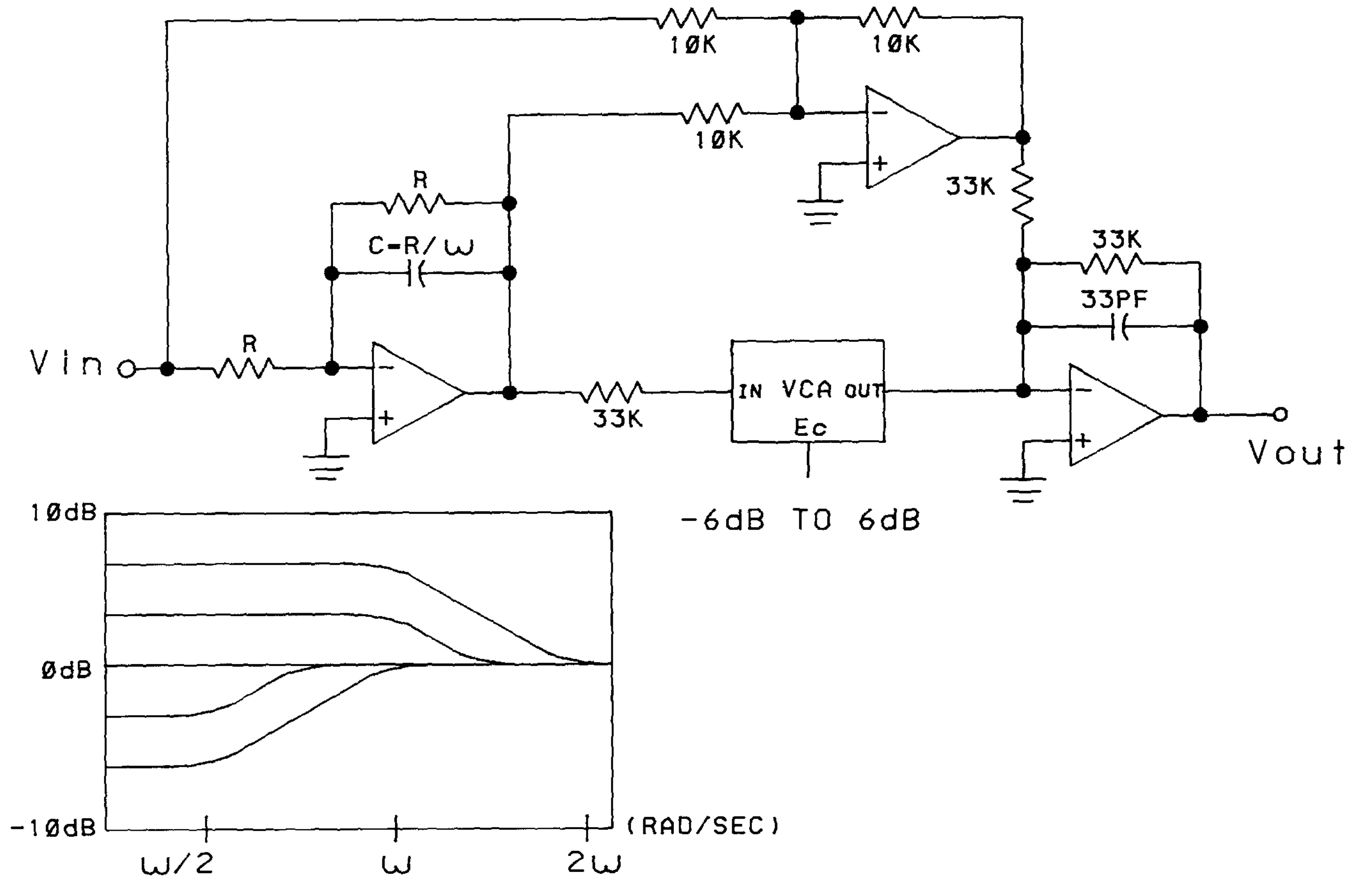
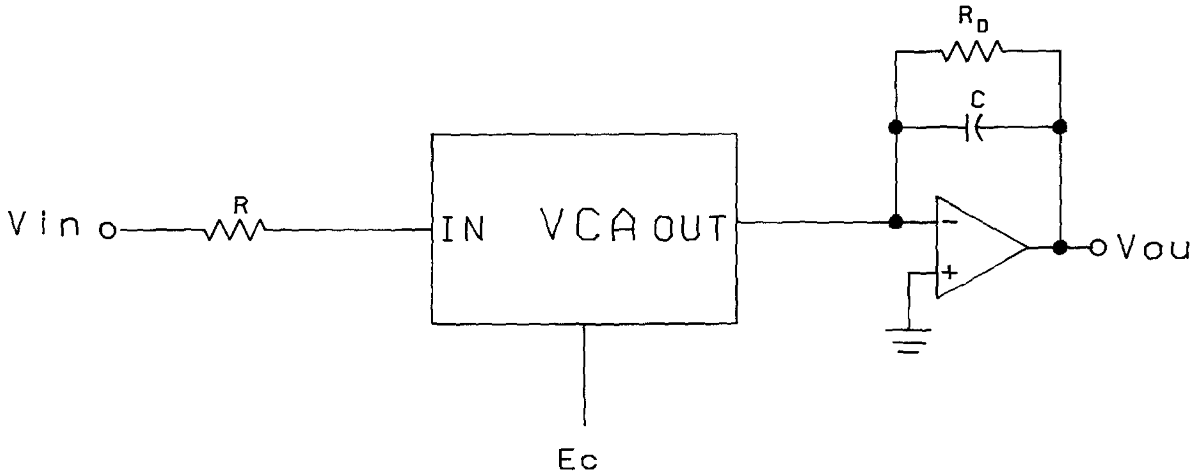


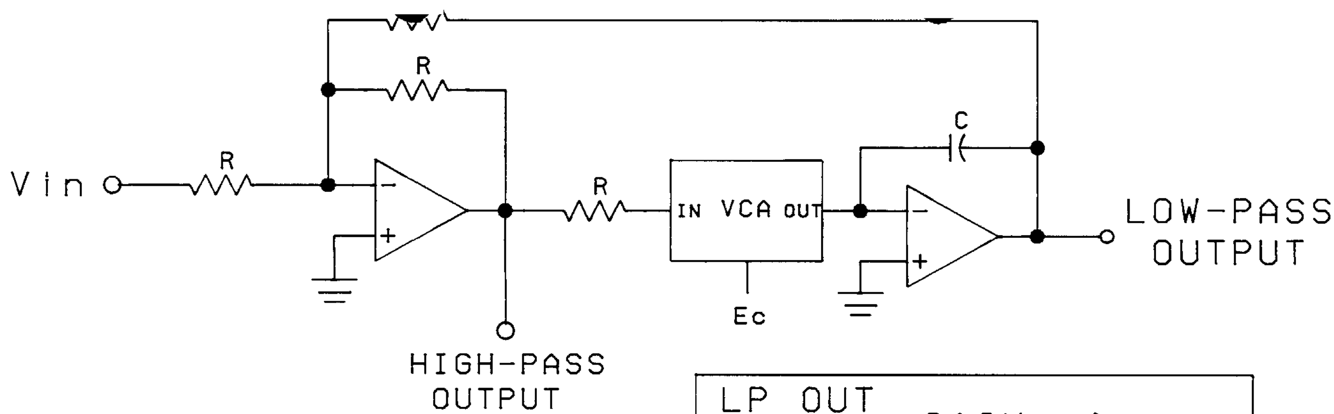
FIGURE 14. SHELVING EQUALIZER



$$\text{ABOVE } \omega = \frac{1}{R_D C}, \quad \frac{V_O}{V_I} = \frac{g}{sCR}$$

WHERE g = GAIN

FIGURE 15. VOLTAGE-CONTROLLED INTEGRATOR



$$\frac{V_{LP}}{V_{IN}} = \frac{g/RC}{s+g/RC}$$

g=GAIN

$$\frac{V_{LP}}{V_{IN}} = \frac{s}{s+g/RC}$$

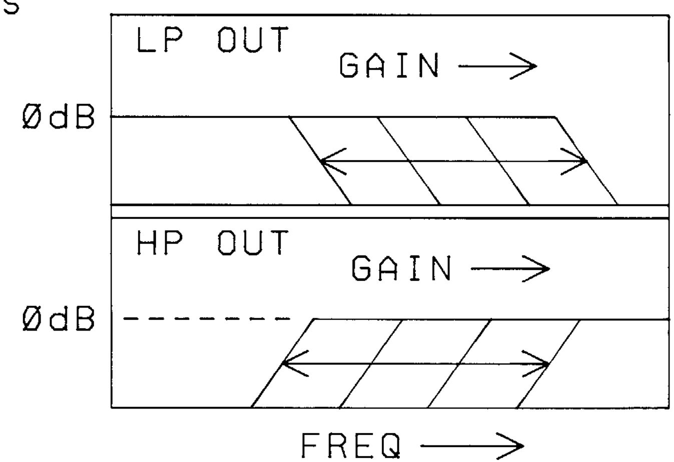
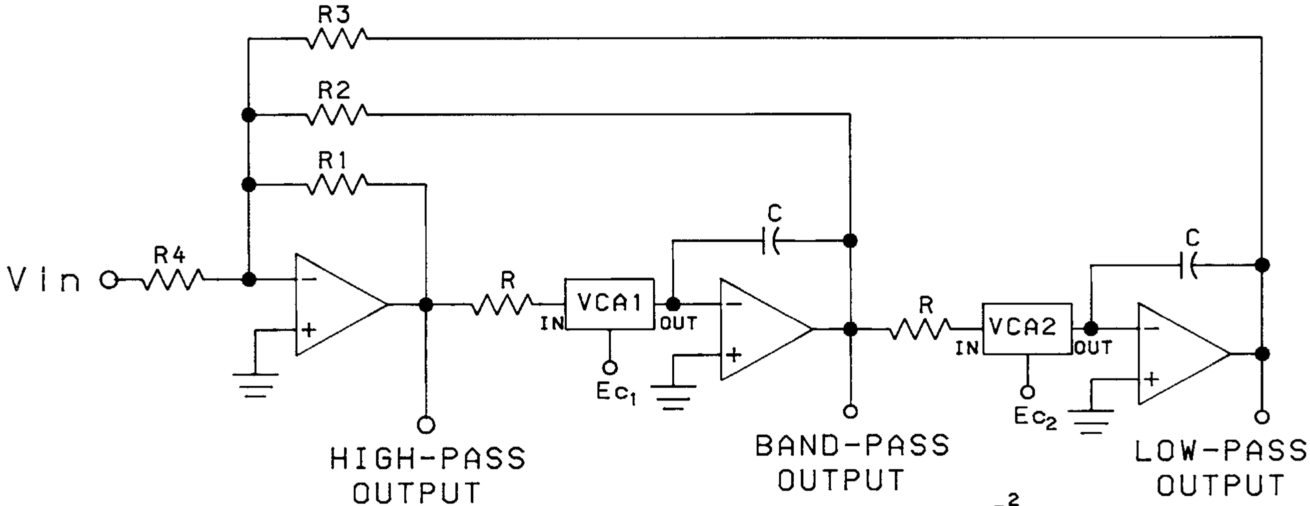


FIGURE 16. SINGLE-POLE VCF



$$\frac{V_{HP}}{V_{IN}} = \frac{S^2}{S^2 + \frac{R_1}{R_2} g_1 SCR + R^2C^2 g_1 g_2}$$

$$R_3 = R_1$$
$$g_1 = GAIN_1$$
$$g_2 = GAIN_2$$

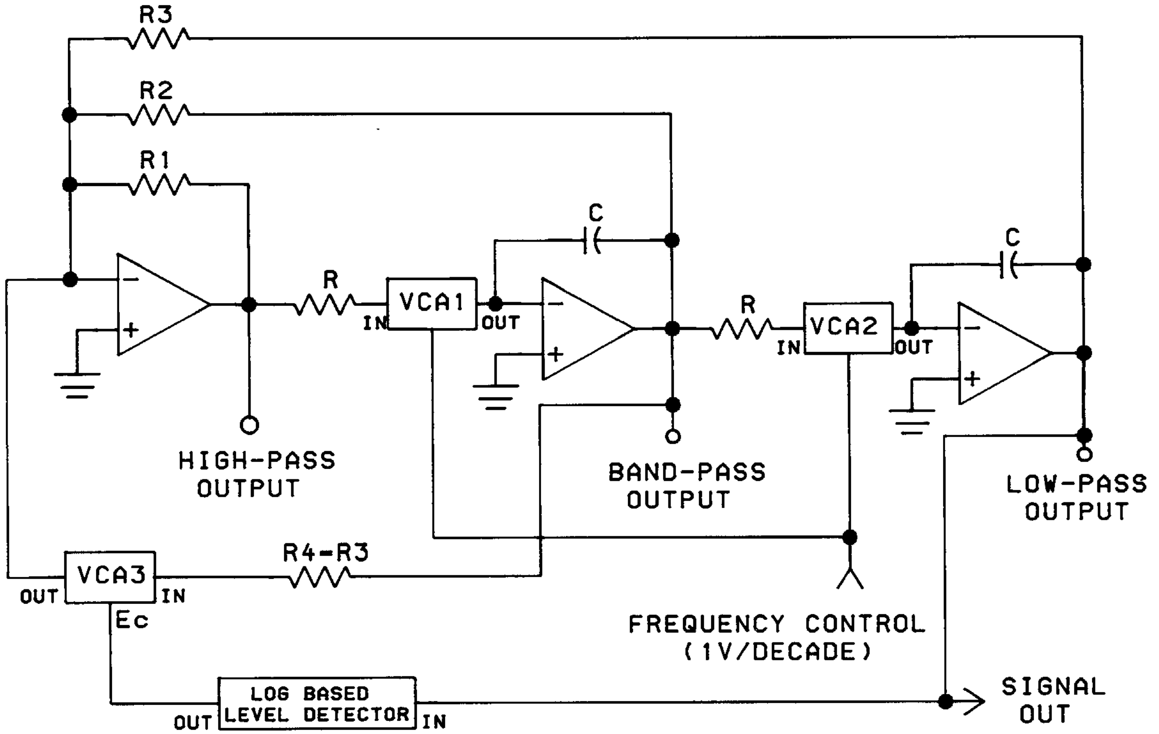
$$W = \frac{\sqrt{g_1 g_2}}{RC}$$

$$\frac{V_{BP}}{V_{IN}} = \frac{g_1 SCR}{S^2 + \frac{R_1}{R_2} g_1 SCR + R^2C^2 g_1 g_2}$$

$$Q = \frac{R_2}{R_1}\sqrt{\frac{g_2}{g_1}}$$

$$\frac{V_{LP}}{V_{IN}} = \frac{g_1 g_2 SC^2R^2}{S^2 + \frac{R_1}{R_2} g_1 SCR + R^2C^2 g_1 g_2}$$

FIGURE 17. SECOND-ORDER STATE-VARIABLE VCF



Q BECOMES INFINITE WHEN Ec AT VCA3 IS ØV.Q IS REDUCED FOR NEGATIVE GAINS AT VCA3,INCREASED BEYOND INFINITY FOR POSITIVE GAINS AT VCA3.

FIGURE 18. VOLTAGE CONTROLLED SINE WAVE OSCILLATOR