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NAVSWC TR 90-180

AN ALTERNATIVE TO OPERATIONAL AMPLIFIERS

BY ARTHUR D. DELAGRANGE

UNDERWATER SYSTEMS DEPARTMENT

1 JUNE 1990

NAVAL SURFACE WARFARE CENTER

Dahlgren, Virginia 22448-5000 ● Silver Spring, Maryland 20903-5000

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FOREWORD

Operational amplifiers are the mainstay of analog (linear) electronics. Alternatives have never been seriously considered. Today there is an ever-increasing push for high speed. This report argues that operational amplifiers are not well suited to high speed and presents an alternative, fixed-gain amplifiers. Typical applications are shown and an approach for designing them suggested.

Approved by:

J. E. Goeller

J. E. GOELLER, Deputy Head
Underwater Systems Department

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INTRODUCTION

Operational amplifiers, often abbreviated op-amps, OAs, etc., are extremely popular in the world of analog circuitry. They comprise about half of all sales of analog integrated circuits (also called linear) and presumable half the usage. A list of manufacturers of op-amps has over 20 entries, even though it takes a great deal of sophistication to make one. The D.A.T.A.* book has over 4,000 line entries in the op-amp section. Courses and books always start with op-amps, and many (unfortunately) do not even mention other types of analog circuits. It may come as a surprise that op-amps are actually not necessary--all known op-amp circuits (including comparators) can be duplicated with another type of device.

WHY NOT OP-AMPS?

If op-amps had not already been built and someone told me to design a signal-processing amplifier with gain on the order of a million that would be stable with the output connected to the input, I would tell them to go fly a kite, preferably in a thunderstorm. Then I would find out what was really needed and look for another way to do the job. Designing a device with a gain of a million to make a circuit with a gain of one is like driving a carpet tack with a sledgehammer.

It can be done, and manufacturers say they have succeeded well, pointing to the list of devices already mentioned here. But have they? Op-amps are the slowest semiconductor devices I can think of offhand. At the beginning of every specification ("spec") sheet is a very impressive "gain" figure--specified at direct current (dc). It is mostly unusable for several reasons: at dc we have offset voltage and drift that almost always limit accuracy, not gain. Since information is proportional to bandwidth and dc is zero frequency, there is no information at dc. For a 741, the most common type, the dc spec is only good to about 10 Hz, below the <u>bottom</u> of the audio range. (Newer designs tend to be about an order of magnitude faster, roughly up to the speed of rotating <u>machinery</u>.)

Further down in the spec sheet, speed is addressed by "gain-bandwidth," again an impressive figure, about 1 MHz for 741s. This is the frequency at which the gain drops to unity so, at that point, the op-amp does less than a piece of wire. A gain of 100 to 1,000 is required to have the op-amps deliver performance near that promised by the theory, so divide gain-bandwidth by that much to get useful frequency, i.e.,

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*Registered trademark

1 to 10 kHz for a 741. Sometimes the product is specified at a lower, useful frequency, but watch out. Some, especially the new "high-speed" ones, are not stable in unity-gain configuration, i.e., when you actually try to use it as an op-amp. The notes point out that such a device can be "fooled" or "compensated" to be stable by throwing away gain, the gain they just finished bragging about. To get an honest answer, divide the gain-bandwidth by the minimum closed-loop gain.

After these corrections, the useful max frequency ranges from around 10 kHz for a 741 to a few megahertz (MHz) for some new ones. While analog designers have been talking microseconds, digital designers have been talking nanoseconds. Consequently, most high-speed processing has gone digital, even though digital requires much more bandwidth for a given information rate.

THE ALTERNATIVE--FIXED-GAIN AMPLIFIERS

Instead of using an amplifier having high but inaccurate gain (op-amp), we can use one having low but accurate gain (fixed-gain-amp, abbreviated FGA). Like op-amps, we will assume a differential, high-impedance input and a single-ended, low-impedance output, although the latter will be more important here since we will not have (external) negative feedback. This is the same function as an Instrumentation Amplifier (IA), a classic configuration using two or three op-amps. The IA thus uses devices having a combined gain of a billion or a trillion to achieve a differential, high-input-impedance gain of one or so, sort of like using telephone poles for tent pegs. It is also slow. Therefore, we will not call our device an IA, to avoid confusion. We could alternately call it a Low-Gain Amplifier, but this term has already been used for op-amps of lower-gain (and usually higher speed) than normal. Likewise, we could use the term "Differential Amplifier," but this also has been previously used for something quite different.

For a symbol we will use a triangle within a triangle (see Figure 1), labeled with the gain (more discussion later). Figures 1 through 15 give the most common op-amp circuits and show how they would be realized using FGAs. We will review them here, at the risk of accentuating the obvious.

Inverting and noninverting amplifiers (Figures 1 and 2) require no external components with an FGA, other than possibly a gain-setting resistor (see discussion later), as this is the basic function of the device. Note that the circuits are the same for the FGA but, for the op-amp, the resistor calculation is slightly different and the input impedance is grossly different. The FGA circuits tend to be more symmetrical. Similarly, the summers (Figures 3 and 4) are the same for the FGA but slightly different for the op-amp.

Figure 5 shows instrumentation amplifiers, already discussed. Figure 6 gives (voltage-controlled) current sources. This is the only instance where the op-amp circuit is more symmetrical. Both circuits require well matched resistors and are only marginally stable without a load.

Figures 7, 8, and 9 give integrator circuits. The usual warning about no dc stability applies to all; it is due to the nature of an integrator and not to the circuits themselves. Figure 10 gives differentiators. Similarly, the usual warning about high-frequency noise and instability applies to both, but tends to be worse with the op-amp, as a typical op-amp has 90 degrees of phase shift and so does the feedback network, making a dandy oscillator.

There are many precision rectifier circuits; Figure 11 gives a pair using the current-source circuits to overcome the diode forward drops. The usual precision rectifier circuits require a device that operates as an op-amp in part of its range and as a comparator in the other part. This is a very difficult application since an op-amp must be compensated and a comparator should not be, with the result that an op-amp must be used and it makes a very slow comparator. The FGA, basically, does not have the compensation problem (discussion later).

Crystal oscillator circuits are shown in Figure 12. The FGA tends to be better because it is faster. Crystals resonate at high frequencies (by op-amp standards), and phase lag in op-amps causes the circuit to oscillate off the crystal frequency (or not at all). A comparator is faster but is not satisfactory because it will be determined to oscillate at some frequency, possibly the wrong one. Inductor-capacitor (LC) oscillators can be made by substituting a series LC for the crystal. Resistor-capacitor (RC) oscillators are also possible.

Figure 13 shows function generator circuits. The op-amp circuit really needs one op-amp and one comparator. In the circuit using FGAs, the one labeled infinity actually need only have a gain greater than the attenuation of its hysteresis feedback network so its loop gain is infinite.

The most common filter section (termed "resonator") is the noninverting Sallen-Key circuit shown in Figure 14. Here the op-amp is simply used as a fixed-gain amplifier; this application is really equivalent to Figure 2. Highpass is similar. These circuits can be used to build any all-pole filter (Butterworth, Chebyshev, Bessel).

For filters requiring zeros (elliptic, notch, all-pass), we need a more complicated section. The circuits of Figure 15 are the simplest known to this author. Table 1 gives one possible assignment of values for the op-amp circuit for either highpass or lowpass. Table 2 gives the same for the FGA circuit plus assignments for notch, all-pass, and bandpass. A different op-amp circuit is needed for the latter three.

PERFORMANCE

In attempting to evaluate the FGA technique there is a major problem--integrated circuit FGAs do not exist. The closest device that could be found is a TL592 (equivalent to an NE592 and similar to a UA733). This is a rather old device, not state-of-the-art by any means. It has a true differential input, but the output range does not include ground, so only alternating current (ac)-coupled circuits could be used. It is fairly fast---about 100 MHz, 3dB bandwidth; slew rate is not stated. For comparison, the TL081 family of op-amps was used. These are fairly recent, Field-Effect Transistor (FET) input, about 3 times better bandwidth and 20 times better slew rate than a 741, 3 MHz, and 12 volts/microsecond, respectively.

Figure 16 gives the circuits used for integration. They actually are pseudo-integrators, as pure integrators are not dc stable. Figure 17 shows the performance. The op-amp has difficulty in spite of the fact that an integrator circuit is an ideal application in that the overall response is similar to that of the op-amp, inversely proportional to frequency, so that the excess gain is the same everywhere. The problem is that the sharp rise at the input couples through the passive components into the output and it takes the op-amp awhile to respond and correct the error, evident as spikes on the output. The FGA does much better in spite of and, to some extent, due to having no negative feedback.

Differentiation circuits are shown in Figure 18. An op-amp is marginally unstable in differentiator configuration as it has 90 degrees of phase lag and the feedback network adds another 90 degrees. The FGA does not have that particular problem, but inspection of either circuits reveals infinite gain at high frequency and, indeed, the FGA circuit did require a small capacitor added for stability. Even so, the performance is dramatically different (see Figure 19). The op-amp is virtually unstable.

Figure 20 gives a crystal oscillator circuit for the FGA. The output is shown in Figure 21. Corresponding figures for the op-amp are not shown because it could not be made to work at all.

Figure 22 gives function generator circuits and Figure 23 the performance. The op-amp has lag and overshoot at both the square wave and triangle wave outputs. Not only are the waveforms terrible, but the frequency is way low due to the lags. (The two circuits have different output levels, but oscilloscope gain was adjusted so that the two pictures should have been the same.)

Figure 24 gives the rectifier test circuits and Figure 25 the performance. Due to slew-rate limiting, the op-amp takes a long time to "cross over" so that the first part of each half-cycle is missing. In fact, the output lags so far behind the input that it never hits the true peak.

For a filter circuit, a difficult design problem was used--an elliptic bandpass of approximately octave bandwidth. (This has been reported elsewhere[1,2] but is included here for completeness.)

Circuits are shown in Figures 26 and 27, but note that they are not for the same frequency. Figure 28 shows the performance of the op-amp circuit using component values for 1.6 kHz center frequency and also for 16 kHz, the latter achieved by reducing indicated capacitor values by a factor of 10. At 16 kHz the characteristic is seriously degraded. Figure 29 shows the response of the FGA circuit at 160 kHz. It is nearly ideal, over 10 times as fast as the op-amp circuit. However, there are two problems. As indicated by the dashed line, distortion limits the effective stopband rejection. Also, any significant departure from room temperature caused significant changes in the characteristic (not shown). This is due to the limits of the 592 and not the FGA concept.

DESIGNING AN FGA

This author set out to design an FGA on the theory that if I succeeded at all it would be easy for a experienced IC designer. (The last op-amp I designed used vacuum tubes.) In fact, it would have been fairly easy if changes could be made to an existing monolithic integrated circuit, as the two can be quite similar.

The input (see Figure 30) is a matched differential pair with emitter currents set by a current source pair, here current mirrors reflecting an externally set current. The collector currents of the input pair go to a pair of current mirrors, reflecting them from the positive supply. One of these currents is reflected again from the negative supply, and the two are summed to give a single-ended current out which is dumped into a load (output) resistor. Since the two dc currents summed are of opposite polarity, they cancel, giving zero volts. This voltage is buffered by a complementary emitter-follower to give a low impedance out. Diode-connected transistors cancel out the base-emitter drops to minimize crossover distortion.

An (input) resistor is connected between the emitters of the input transistors so that any differential (input) voltage across them creates a differential (unbalance) current which is reflected through and becomes a (nonzero) current in the load resistor, causing a proportional output voltage. As shown by the equation, the voltage gain is given by the ratio of the two resistors times two, the doubling caused by the differential-to-single-ended conversion.

There are a few more details. The last-mentioned current mirrors must be a Wilson circuit for best matching of its input and output currents; the previous two sets occur in balanced pairs so accuracy is less important. The pair of PNP transistors in the middle of the circuit connected to a bias voltage is necessary so that the two current mirrors connected to the positive rail see the same voltage (cascode configuration), minimizing the effect of finite transistor output impedance (equivalent to finite Early Voltage). Without them offset is considerably worse. The capacitor across the input resistor improves the high frequency response of the circuit. It compensates for capacitance across the output resistor. It is adjusted for flat step response, similar to adjusting a scope probe. It thus must be selected according to the gain used. Note that if the power supplies are interchanged and NPNs and PNPs interchanged, a complementary circuit is obtained.

Table 3 gives an outline of circuit performance. Gain error could be improved by adjusting the gain-setting resistors. Offset voltage may be measured either at the input or output (unity gain) and is due to both output offset current and conventional input offset voltage. Input current is high by conventional op-amp standards but less than some high-speed op-amps. Similarly, input resistance is somewhat low. (FETs could be used as the input transistors to drastically improve both.) Common mode rejection ratio is better than many op-amps at 100 kHz. Signal ranges are inherently comparable to op-amps but are limited at low (external) resistance values. Power supply rejection ratios are somewhat worse than most op-amps, but could probably be improved. Slew rates and rise times are better than most op-amps, even FET types, but settling accuracy is not good due to slow "tails." Bandwidths are quite good. Output impedance could be improved. Distortion was not measurable with the instruments at hand, less than 0.04% total harmonic distortion (THD). It should be good, as the circuit is basically linear.

The circuit would certainly be better in monolithic form. In monolithic form,the emitter ballast resistors would be unnecessary. The breadboard circuit will work without them using monolithic quad transistors and no resistors, but offset is much worse. Three hundred and fifty MHz transistors are used; much faster ones are now available.

Note that if the input resistor is shorted and compensation is added, the circuit becomes an op-amp. The difference between the two is basically this. In the op-amp, all the gain is put together and negative feedback used around the entire amplifier to stabilize the gain. In the FGA, the negative feedback is instead used within each stage, greatly easing the oscillation problem and eliminating the need for compensation.

The design techniques needed thus are very similar to those for op-amps, and existing technology should be adequate to make a good FGA. In addition, there are available a number of integrated-circuit tricks available for improvements to the circuit, such as decreasing the input current or decreasing the output impedance.

Low-frequency specs can be improved by adding a conventional op-amp to form a compound amplifier, as shown in Figure 31 for a voltage follower. Offset, gain error, and rejection ratios become that of the op-amp. Output impedance is divided by the op-amp gain.

GAIN SETTING

The circuit, as shown, required nine pins, which is inconvenient since the standard op-amp package only has eight. One answer is to preset the current internally. Another is to preset the gain; this is attractive because it could be trimmed by the manufacturer to good accuracy. It could always be reduced by external techniques, i.e., use of Thevenin equivalents. With the exception of the function generator, which could be changed, no circuit shown required a gain of more than three. However, there is a modification to the low-pass-with-notch filter section (shown in Figure 32) to allow the use of equal capacitors (highly desirable in sensitive filters) which requires a gain of six maximum. Thus, a gain of three would satisfy most applications, and one with a gain of six would cover all shown here. Another argument for internal resistors is that capacitance at either input or output resistor causes "tails." A compromise might be to have the resistors internal but bring one or more pins out for optional adjustment.

For the device used in the demonstration circuits (type 592), gain is set by a single external resistor. It can be set quickly and accurately with an ac signal source and accurate voltmeter. The problem is that it drifts with temperature. This could be improved by using a resistor of offsetting temperature coefficient. The problem is less severe in the proposed circuit (Figure 30) because gain is determined basically by a ratio of two resistors, both external or both internal.

WHAT CHANCE DO FGAS HAVE?

Discussion of the FGA concept with magazine editors and manufacturers generated a tidal wave of apathy. The usual response was that these jobs could be done by op-amps. This is true in theory, but virtually every claimed advantage of op-amps falls apart at high frequency. The second was that an FGA can be made with two or three op-amps. Again true, but this simply combines the disadvantages of both.

The industry has a tremendous investment in op-amps--development, stock, and education. There is tremendous inertia and resistance to new developments. Consider how long most IC manufacturers delayed making decent PNP transistors when it was clearly doable and offered significant advantages. Nevertheless, when it finally happened, many jumped on the bandwagon. Also, current-feedback amplifiers have received considerable acceptance because they are somewhat faster than conventional op-amps, even though there are some disadvantages. They do have the psychological advantage that the overall circuits look the same. However, FGAs may have a chance, too.

CONCLUSION

It has been said that if Henry Ford hadn't done so well with the Model T, we would be driving electric cars. If the early analog pioneers had gotten interested in fixed-gain amplifiers instead of infinite-gain amplifiers, we would probably be using FGAs instead of op-amps. Whether or not FGAs succeed will depend on (1) whether someone decides to market them, develops techniques, gets the bugs out, and alerts potential users and, then, (2) how useful they prove to be.

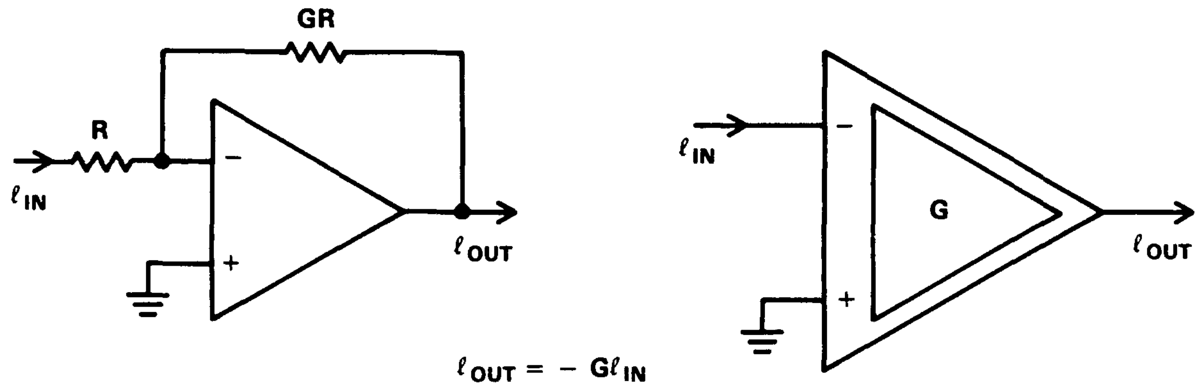


FIGURE 1. INVERTING AMPLIFIERS

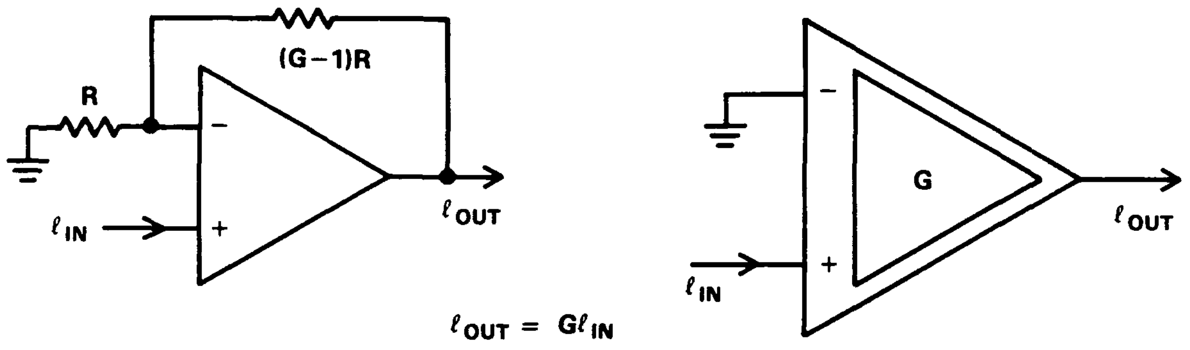


FIGURE 2. NONINVERTING AMPLIFIERS

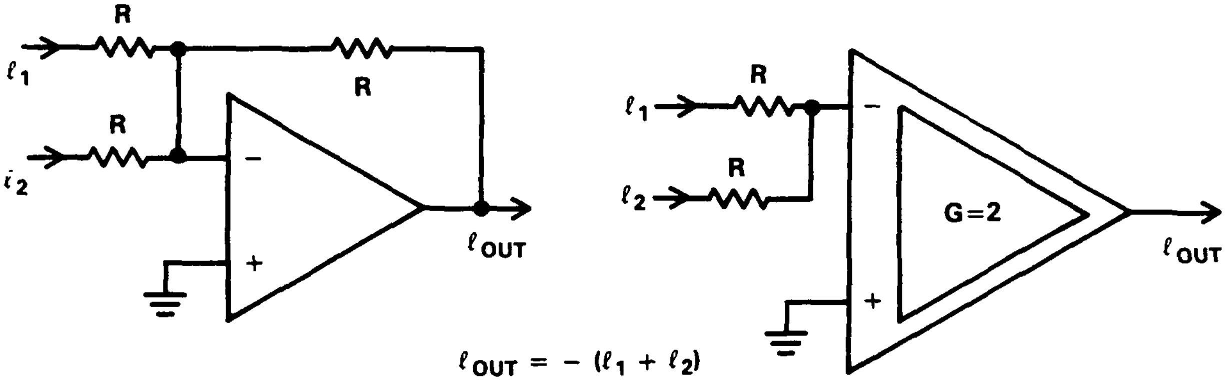


FIGURE 3. INVERTING SUMMERS

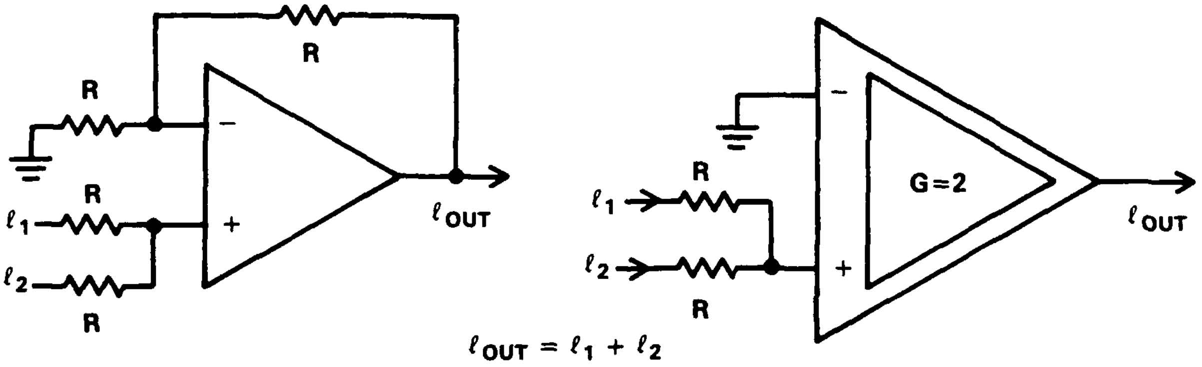
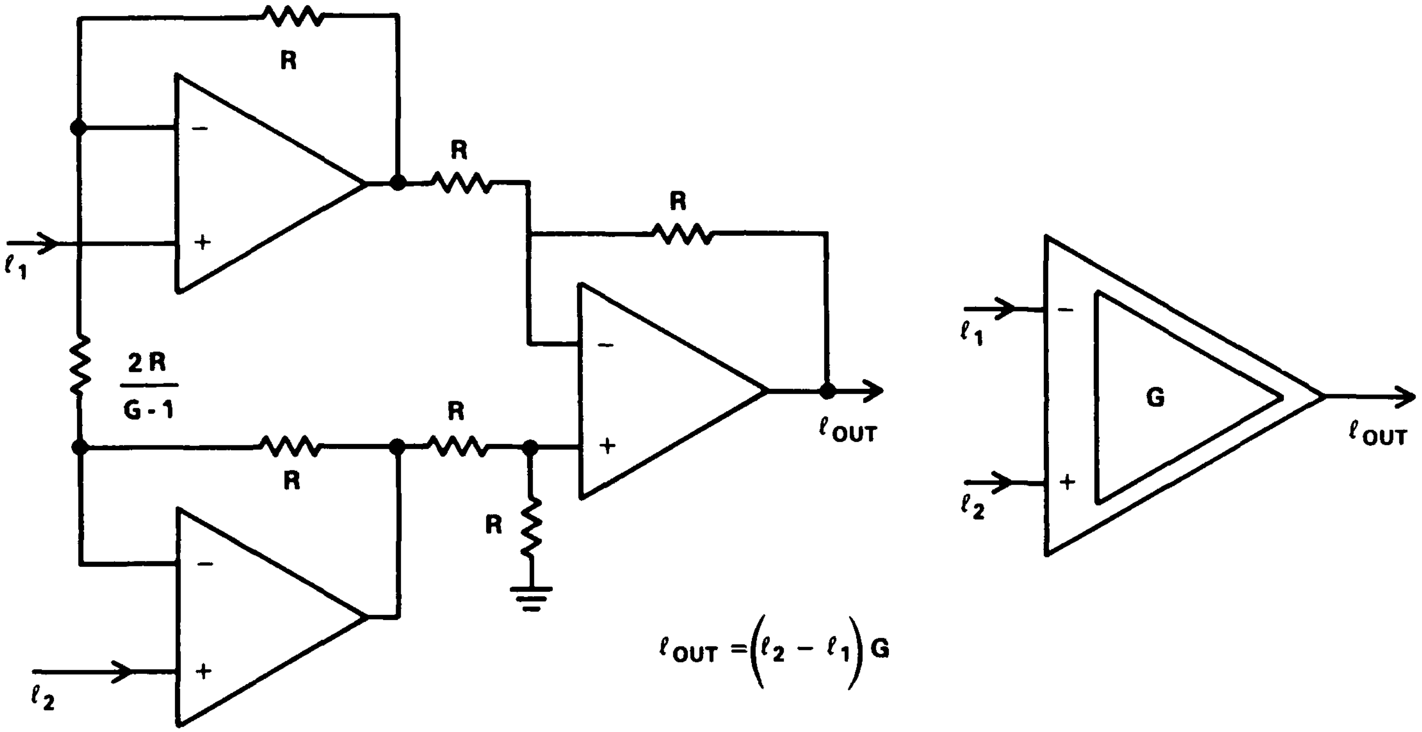


FIGURE 4. NONINVERTING SUMMERS



$$\ell_{OUT} = \left(\ell_2 - \ell_1\right) G$$

FIGURE 5. INSTRUMENTATION AMPLIFIERS

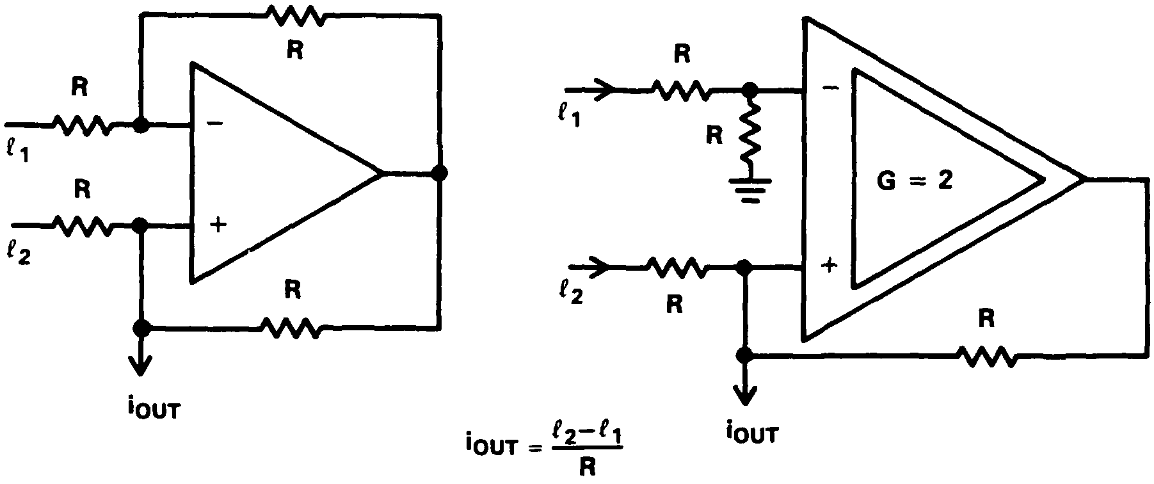


FIGURE 6. CURRENT SOURCES

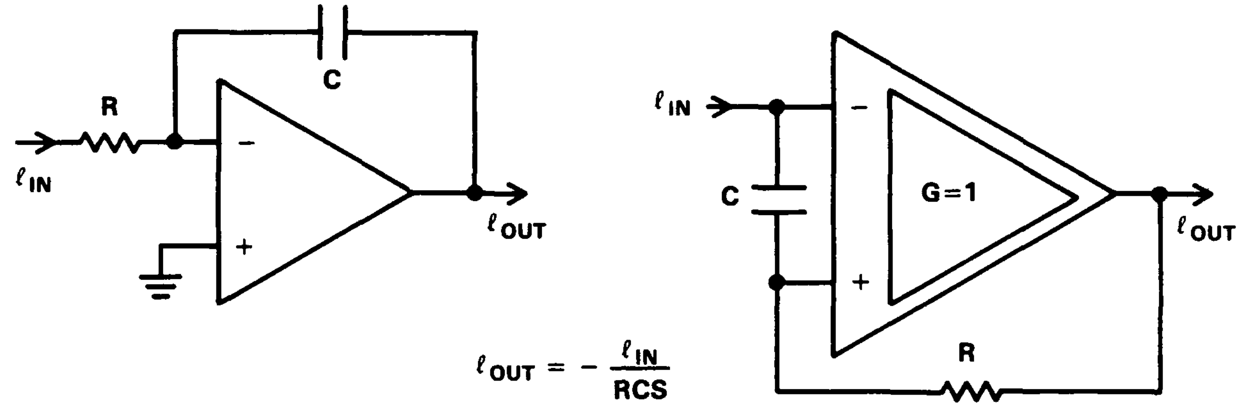


FIGURE 7. INVERTING INTEGRATORS

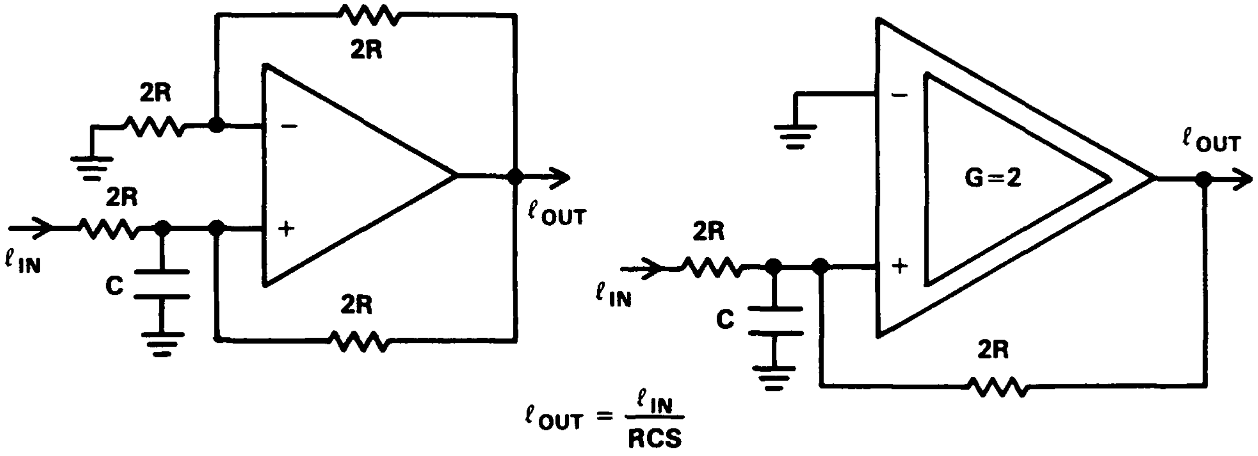


FIGURE 8. NONINVERTING INTEGRATORS

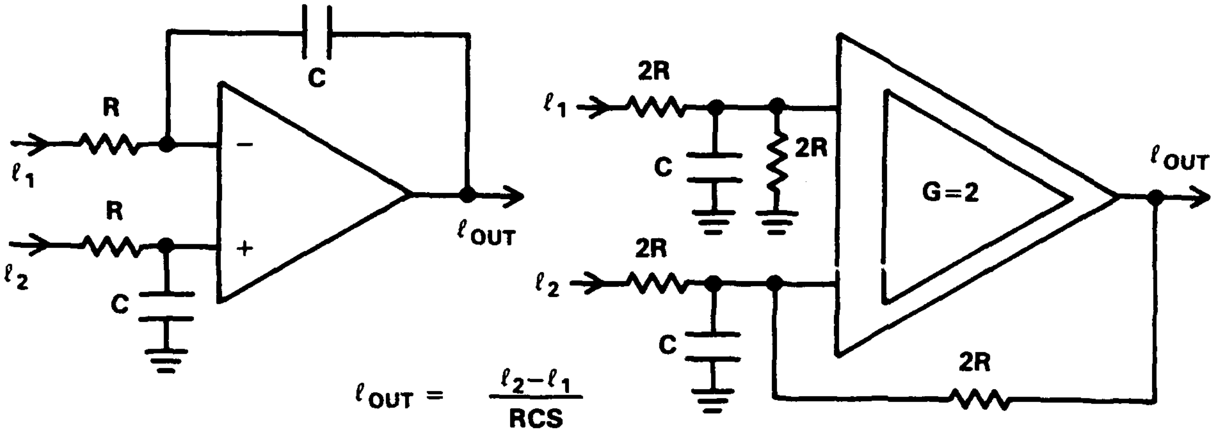
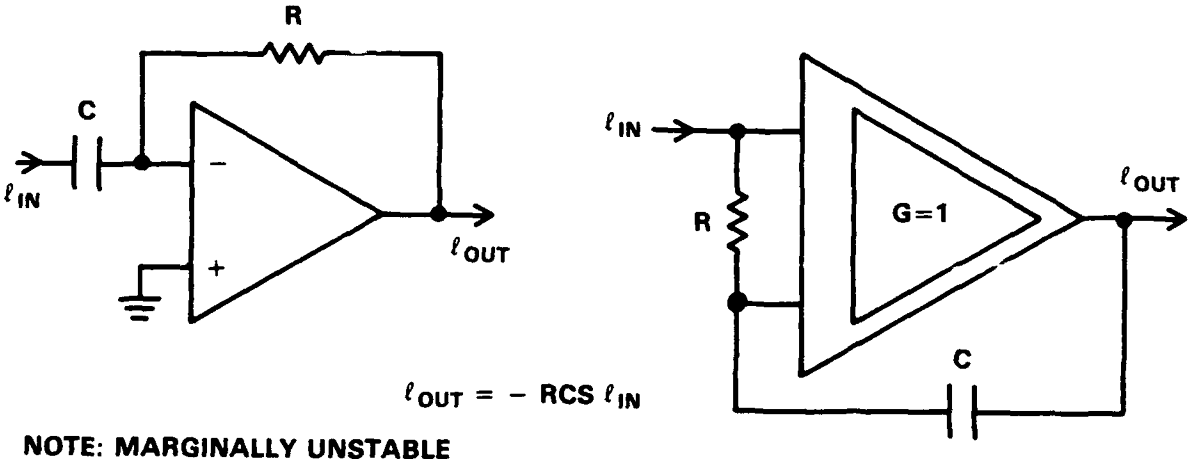
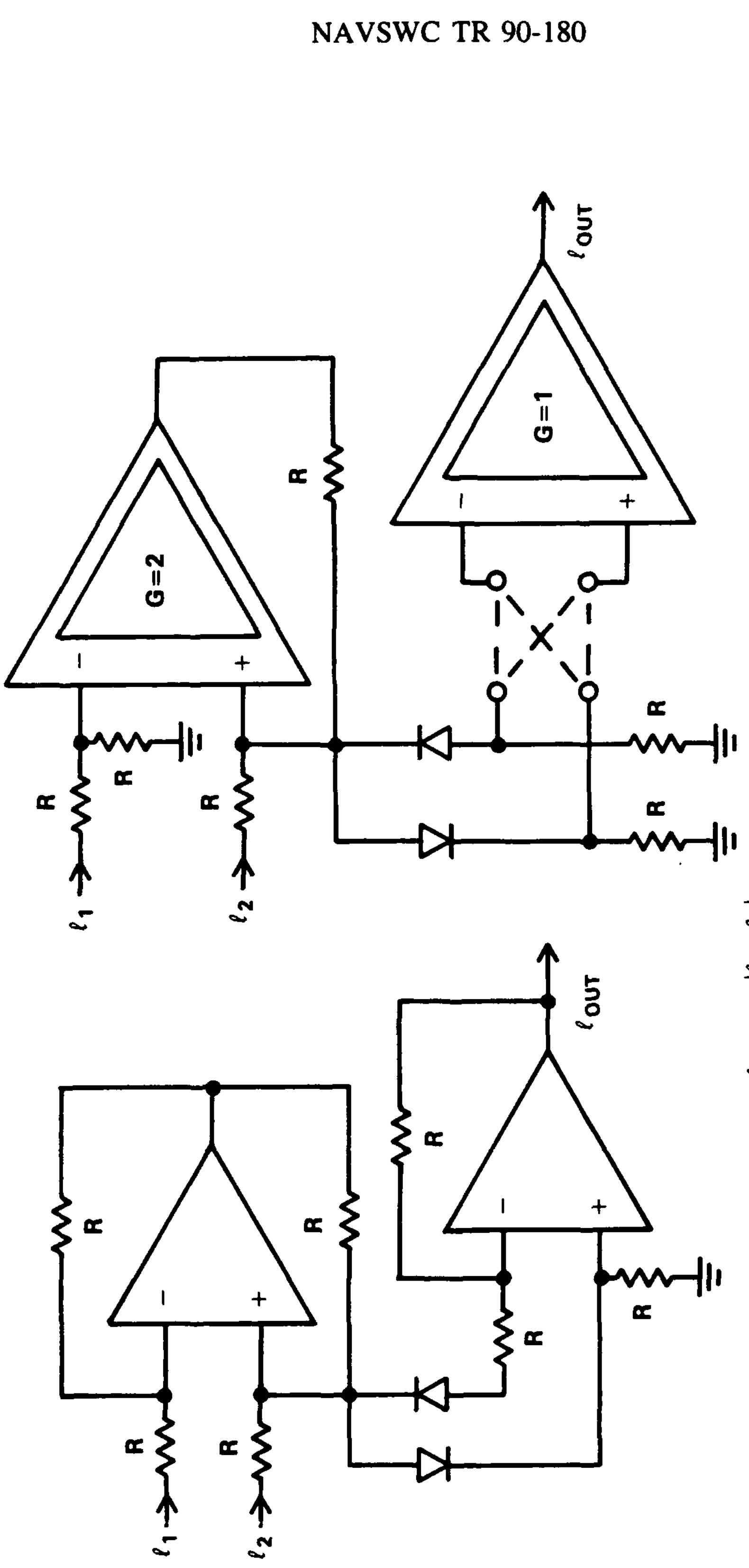


FIGURE 9. DIFFERENTIAL INTEGRATORS



NOTE: MARGINALLY UNSTABLE

FIGURE 10. INVERTING DIFFERENTIATORS



$\ell_{OUT} = |\ell_2 - \ell_1|$

FIGURE 11. PRECISION RECTIFIERS

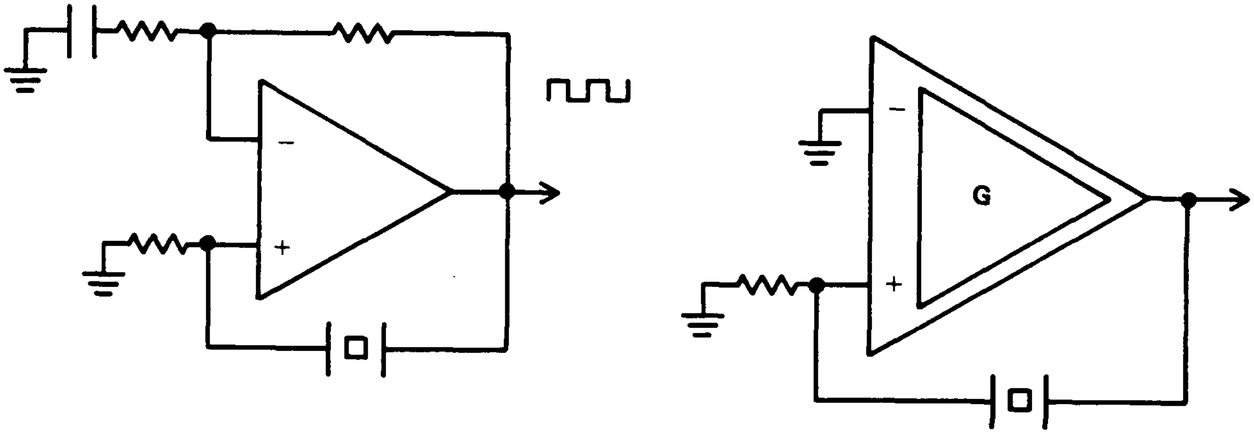


FIGURE 12. CRYSTAL OSCILLATORS

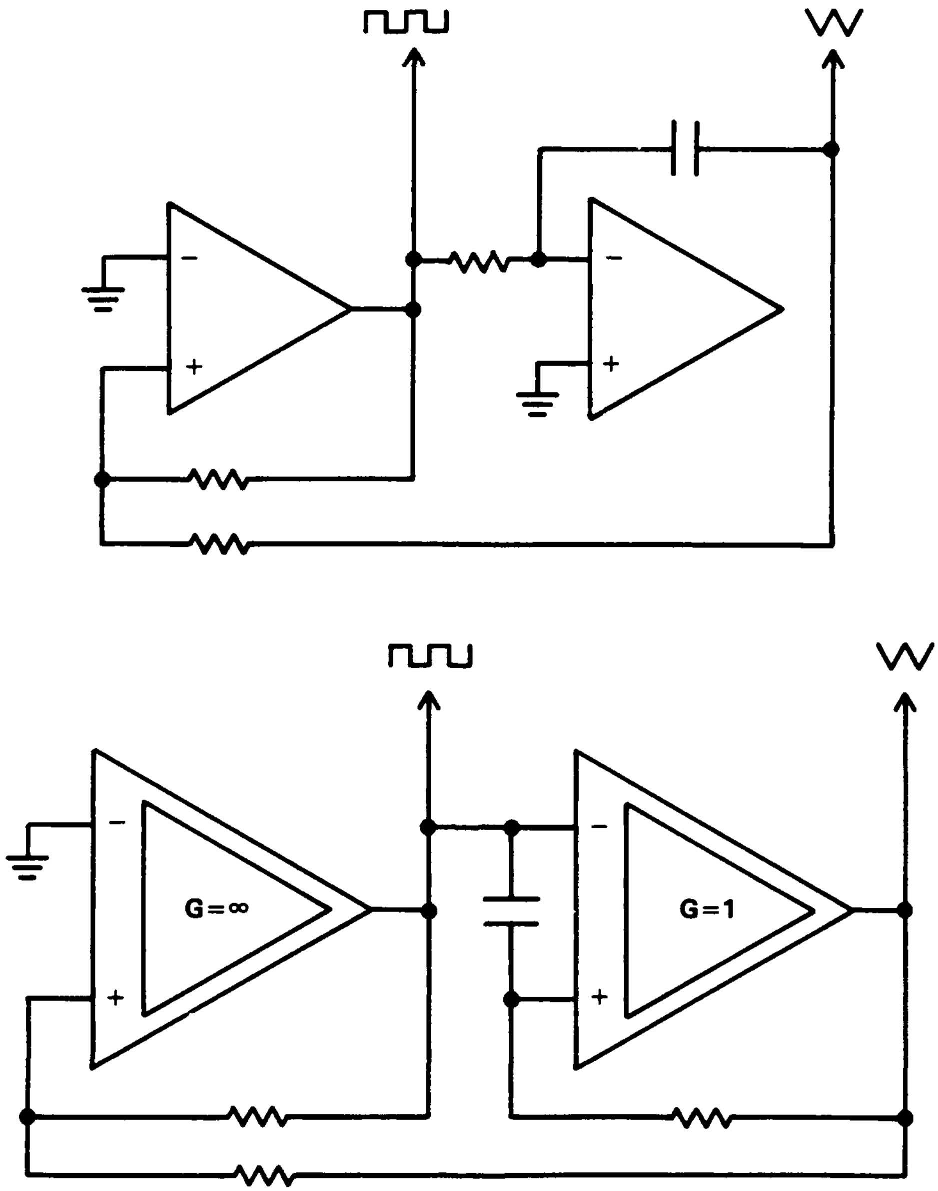


FIGURE 13. FUNCTION GENERATORS

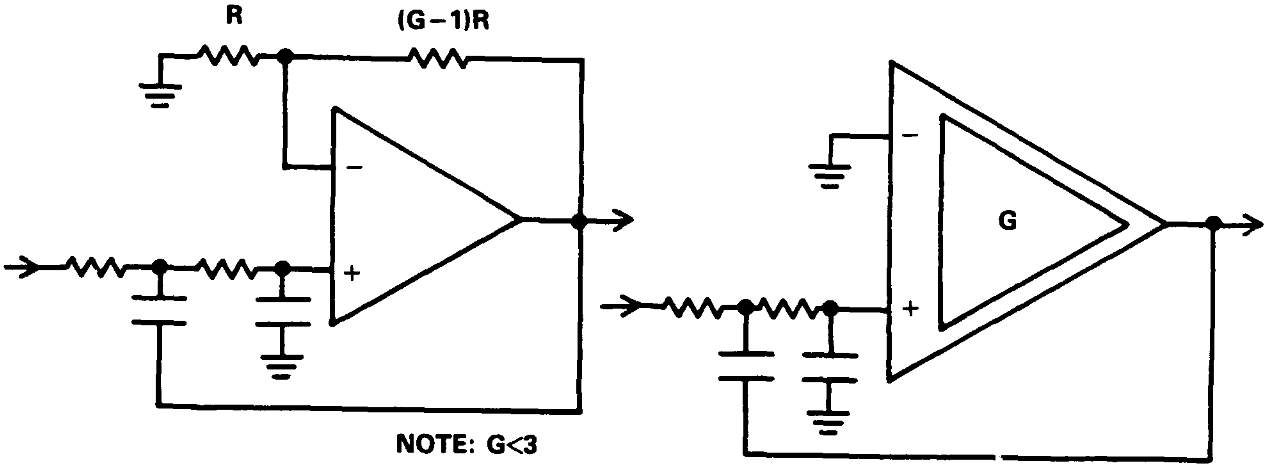
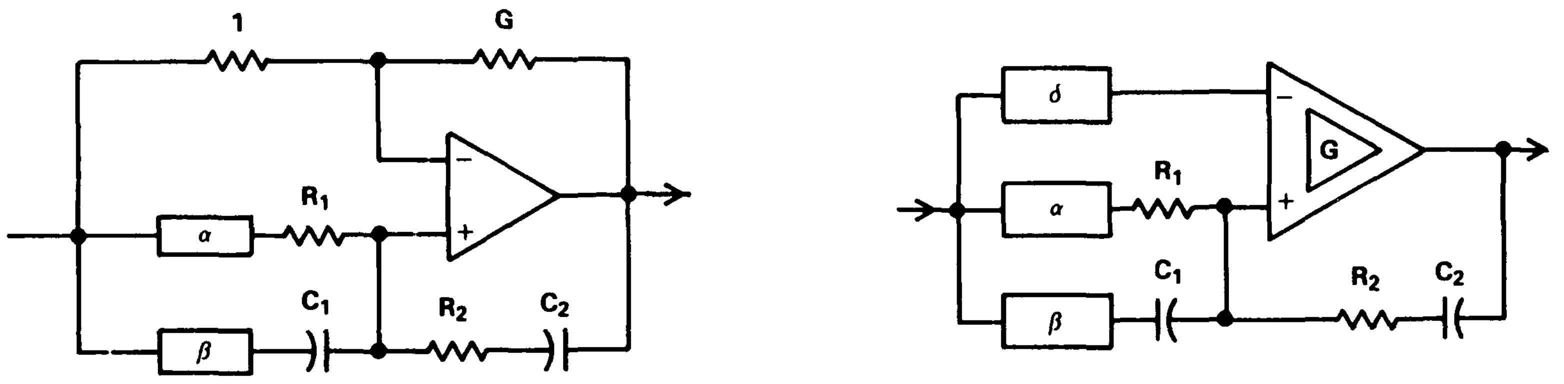
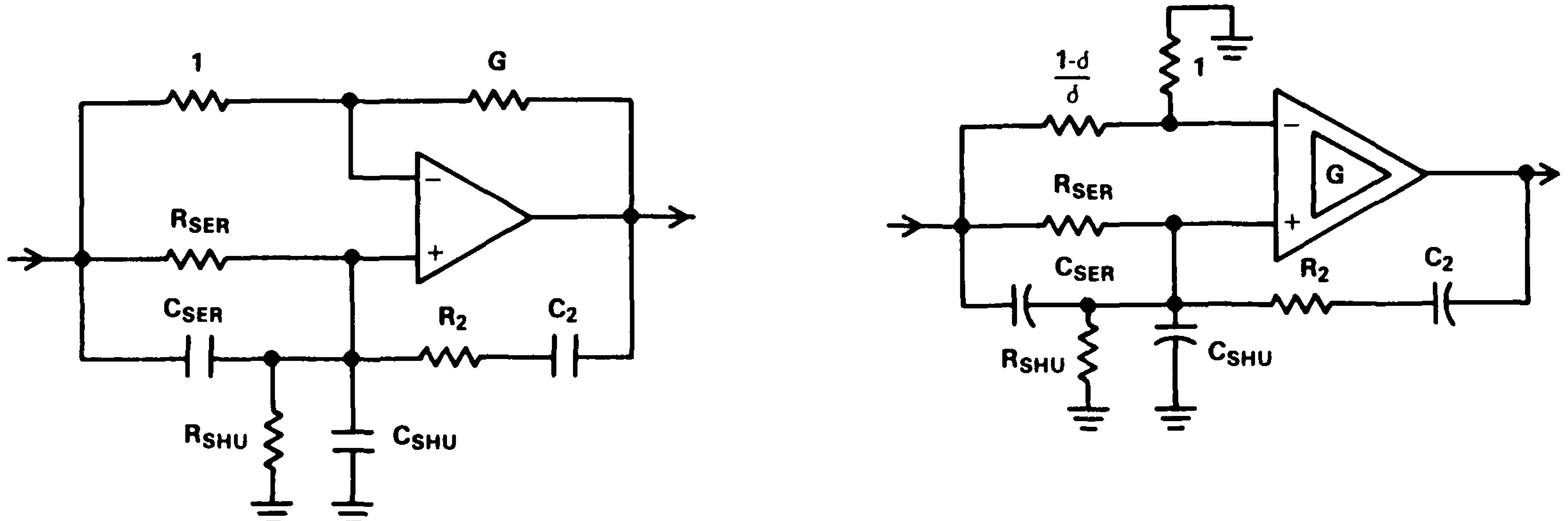


FIGURE 14. SALLEN-KEY RESONATORS



A. BASIC CIRCUITS



B. COMPLETE CIRCUITS

FIGURE 15. RESONATOR CIRCUITS WITH ZEROS

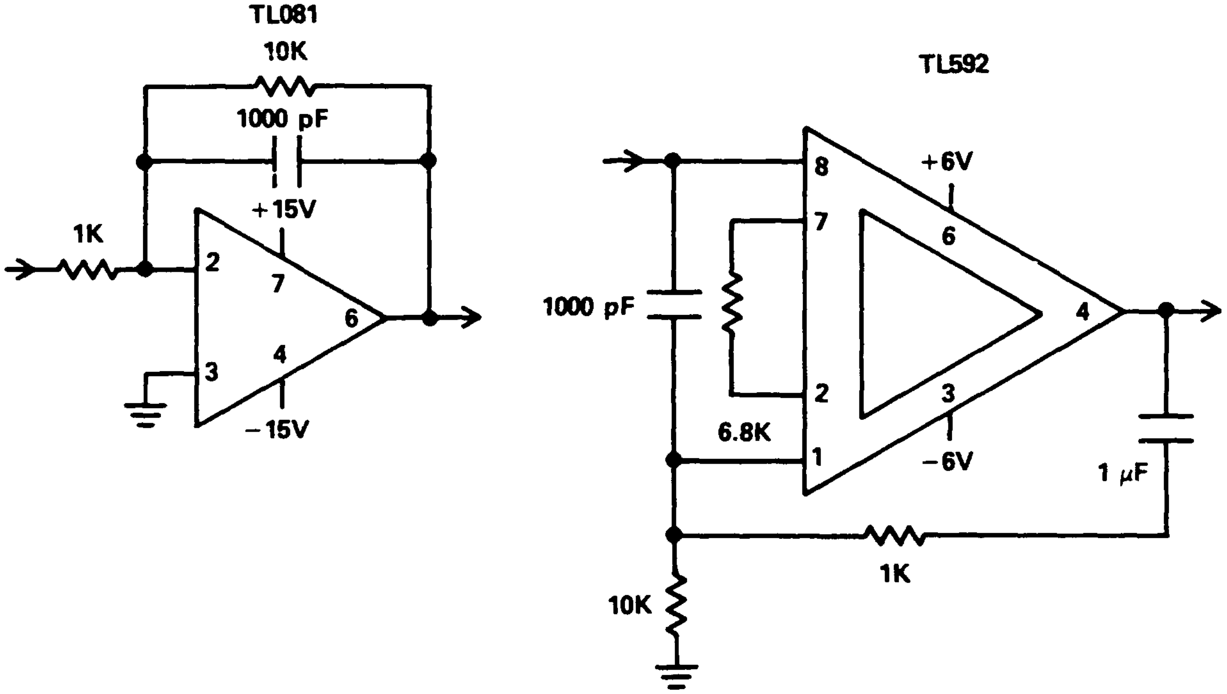
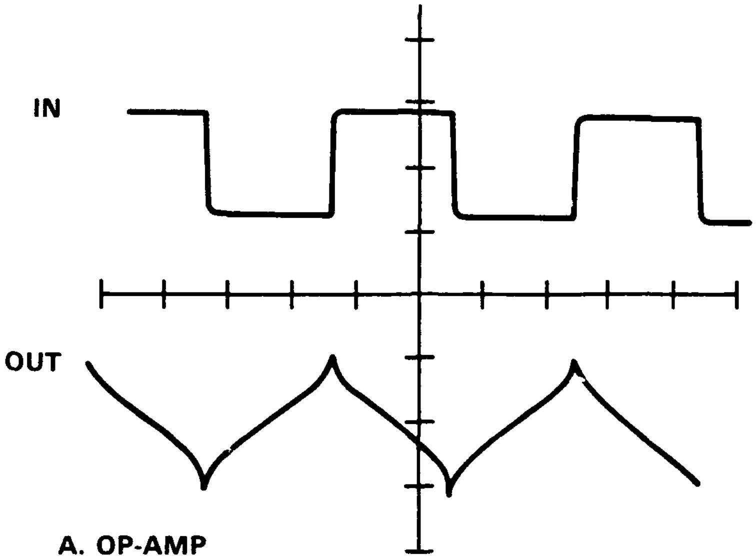
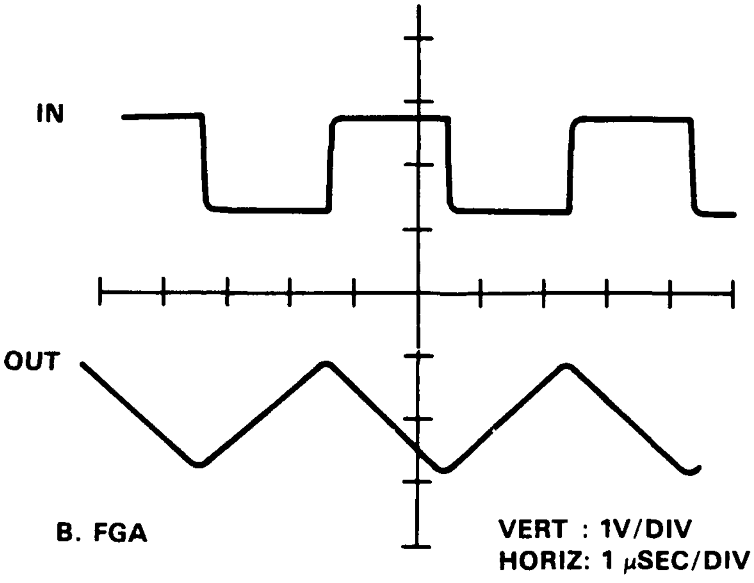


FIGURE 16. INTEGRATOR TEST CIRCUITS

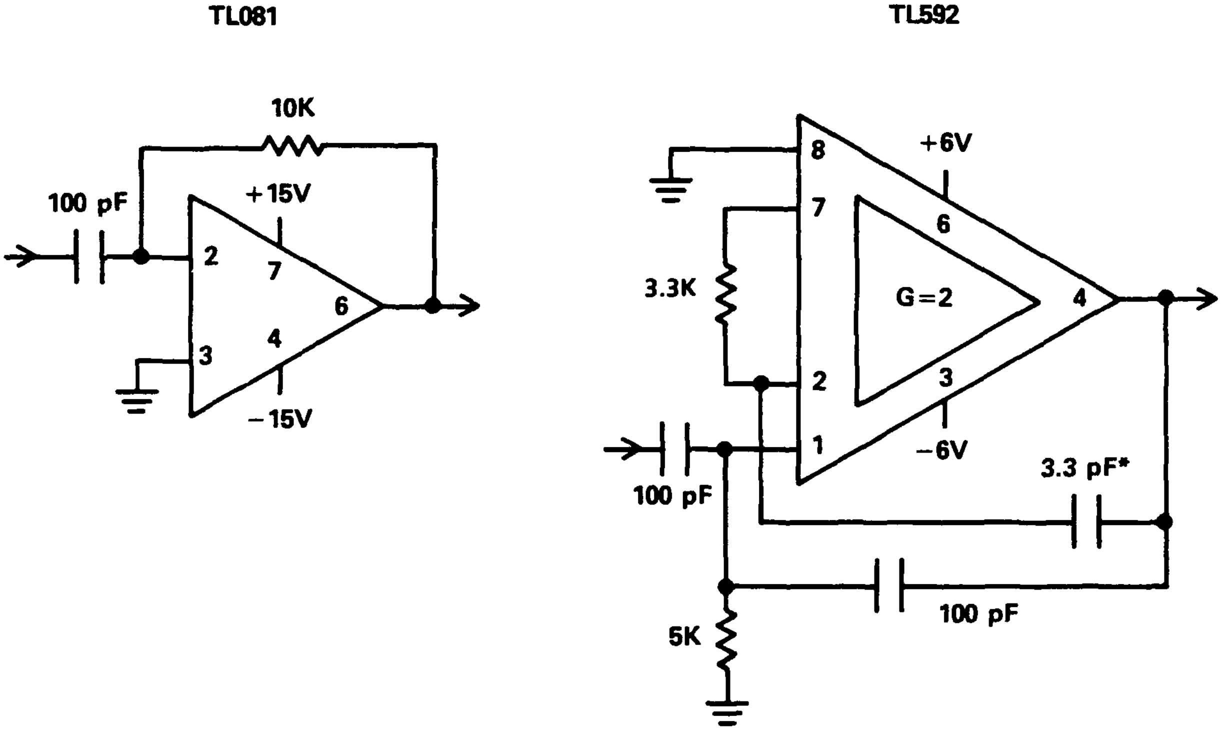


A. OP-AMP



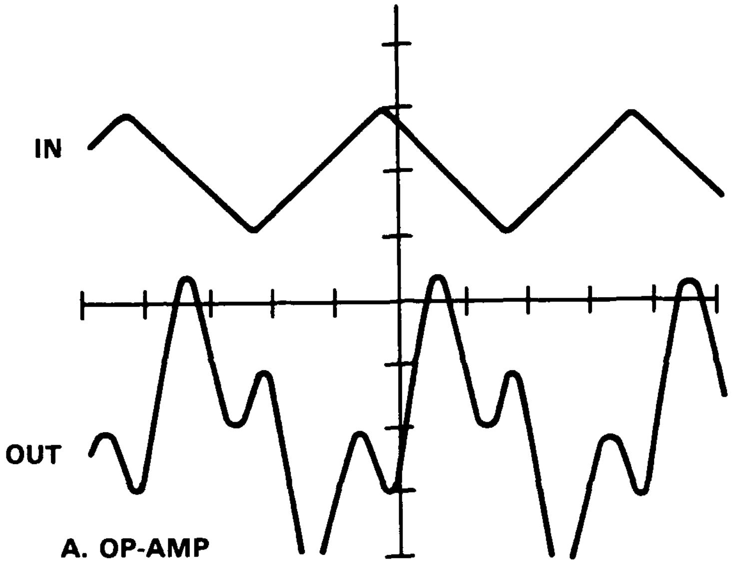
B. FGA

FIGURE 17. INTEGRATOR PERFORMANCE

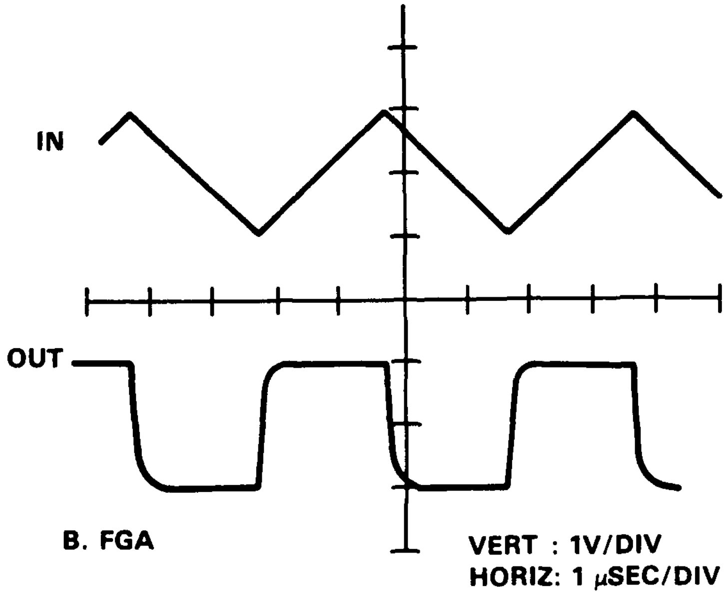


*PREVENTS HIGH-FREQUENCY OSCILLATIONS

FIGURE 18. DIFFERENTIATOR TEST CIRCUITS

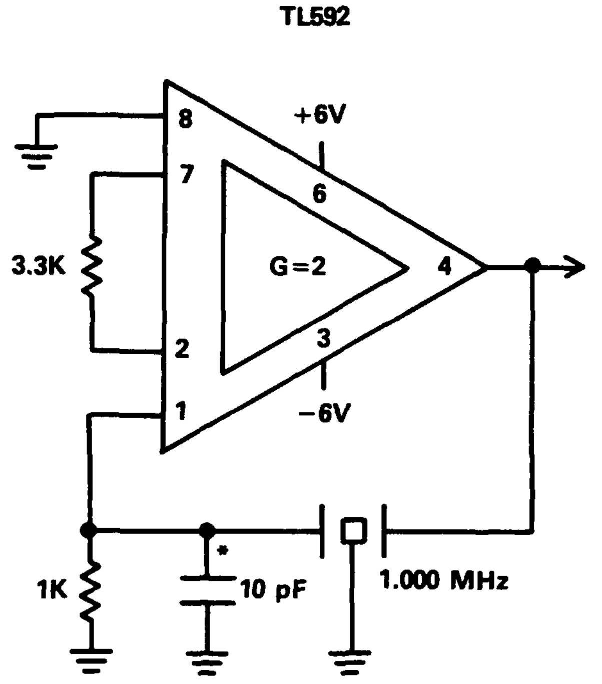


A. OP-AMP



B. FGA

FIGURE 19. DIFFERENTIATOR PERFORMANCE



*PREVENTS HIGH-FREQUENCY OSCILLATIONS

FIGURE 20. CRYSTAL OSCILLATOR TEST CIRCUIT

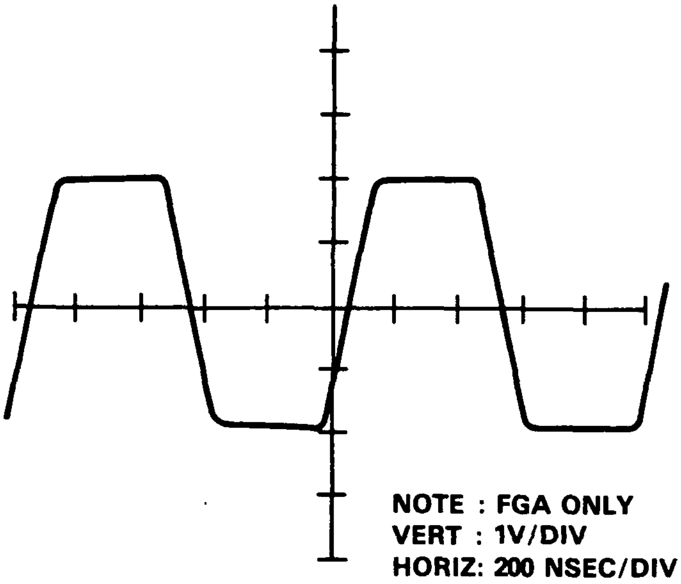


FIGURE 21. CRYSTAL OSCILLATOR PERFORMANCE

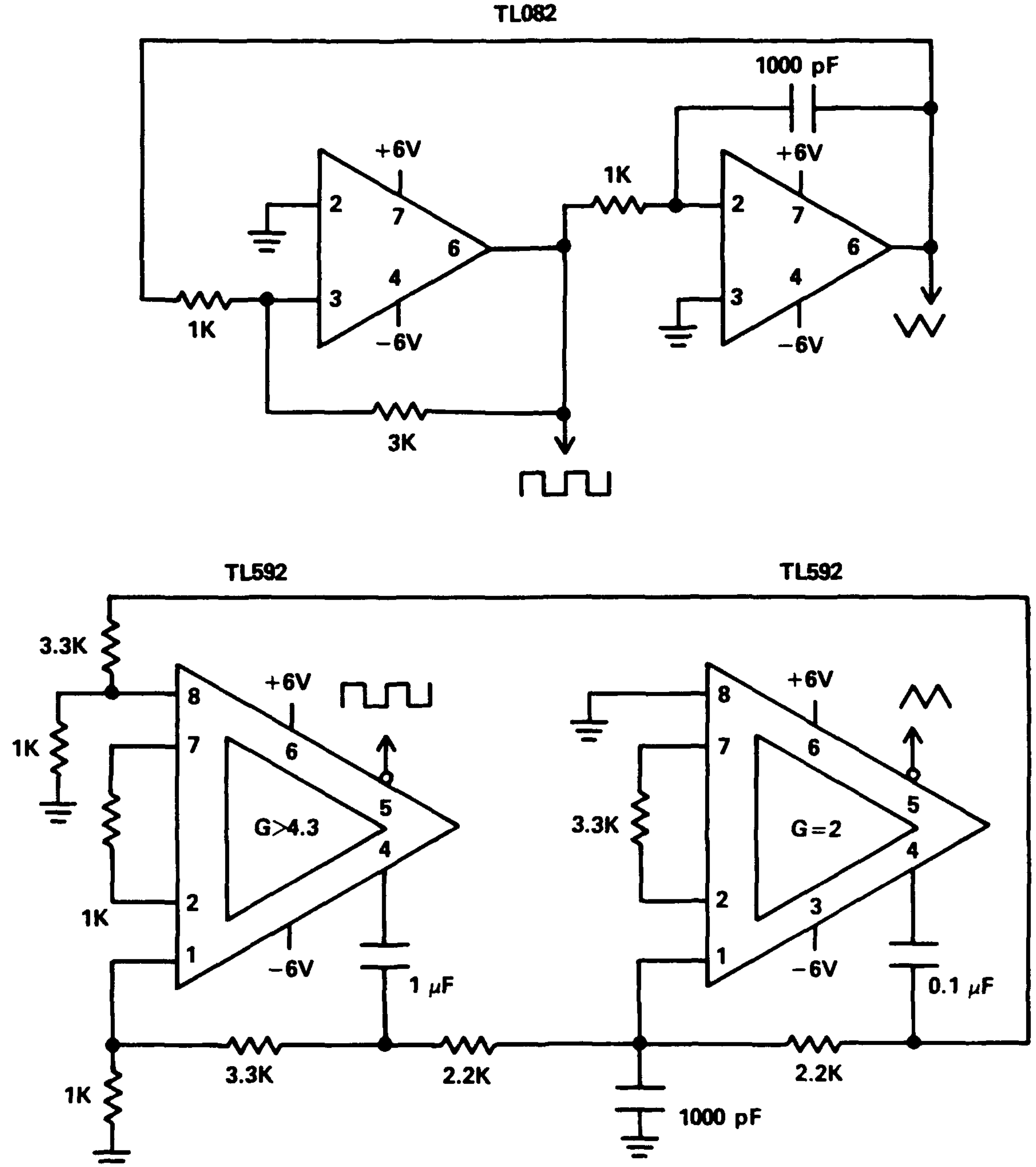
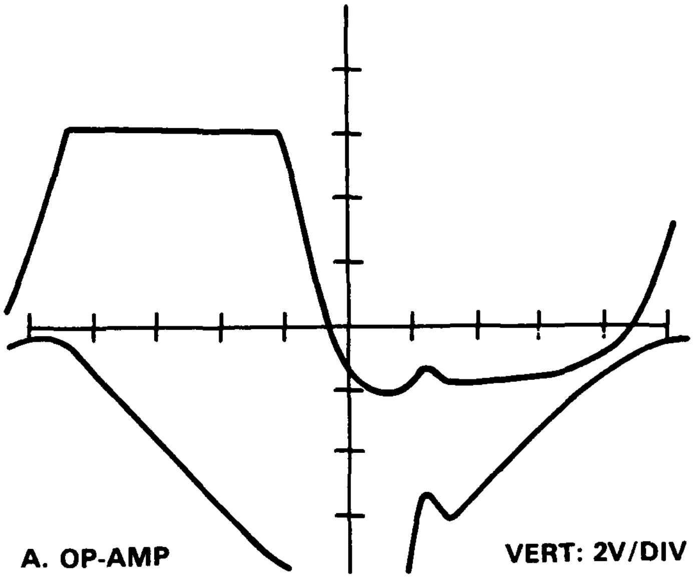
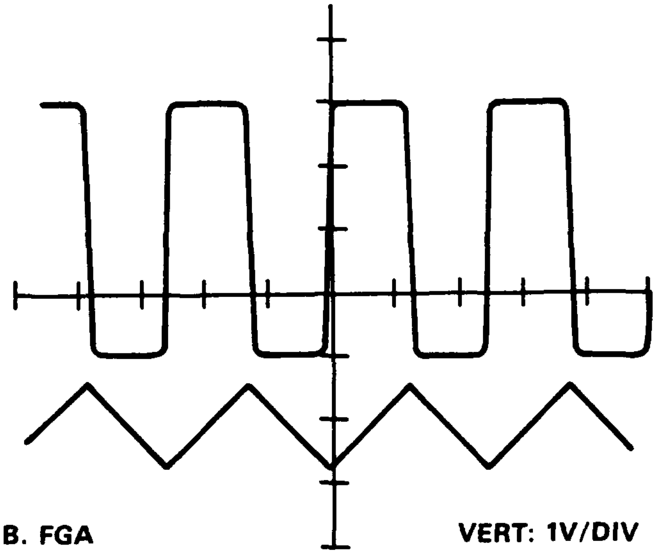


FIGURE 22. FUNCTION GENERATOR TEST CIRCUITS



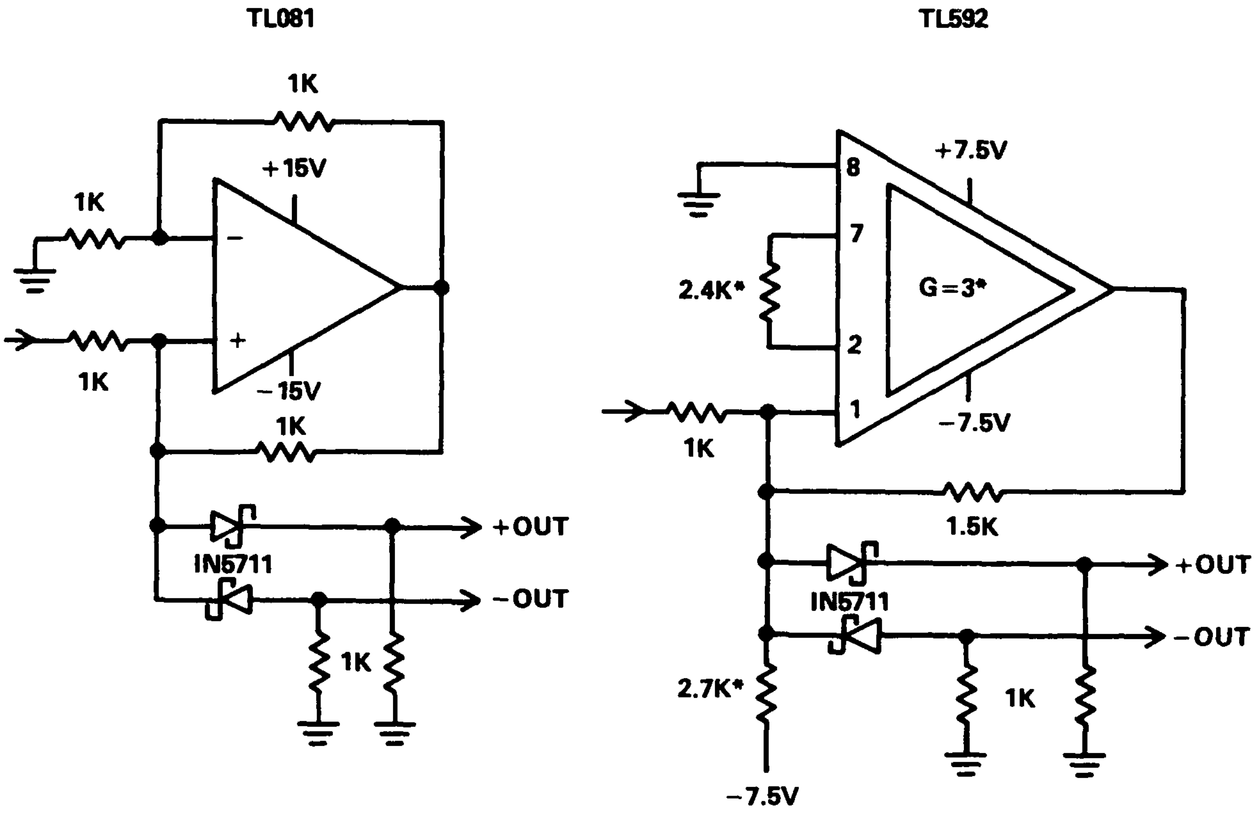
A. OP-AMP



B. FGA

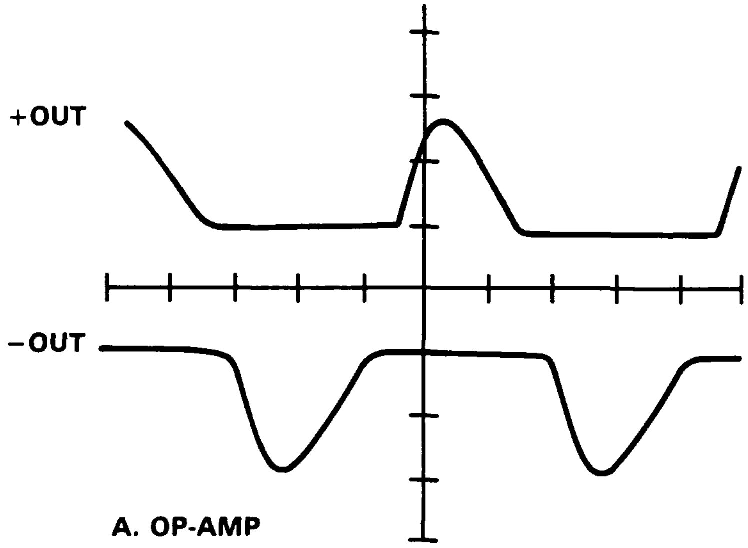
HORIZ: 500 NSEC/DIV

FIGURE 23. FUNCTION GENERATOR PERFORMANCE

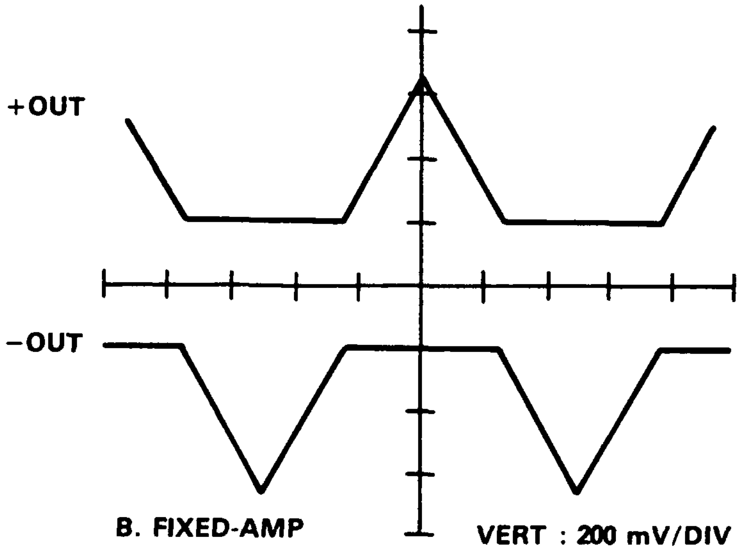


*ADJUSTED

FIGURE 24. RECTIFIER TEST CIRCUITS



A. OP-AMP



B. FIXED-AMP

FIGURE 25. RECTIFIER PERFORMANCE

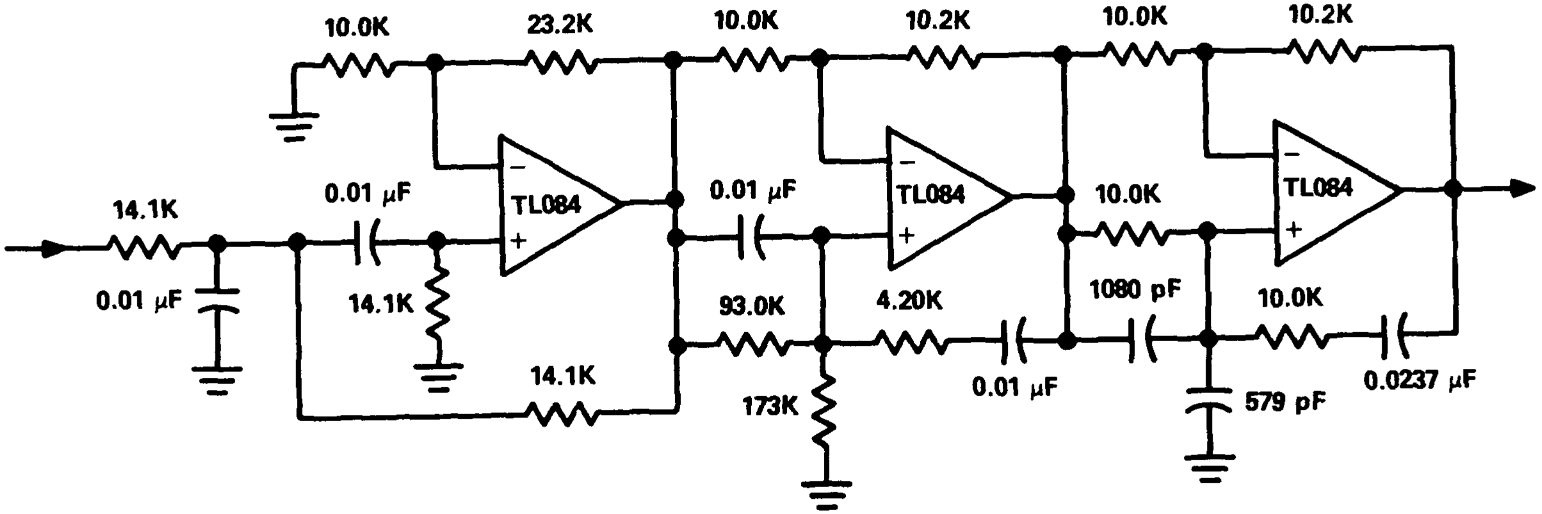
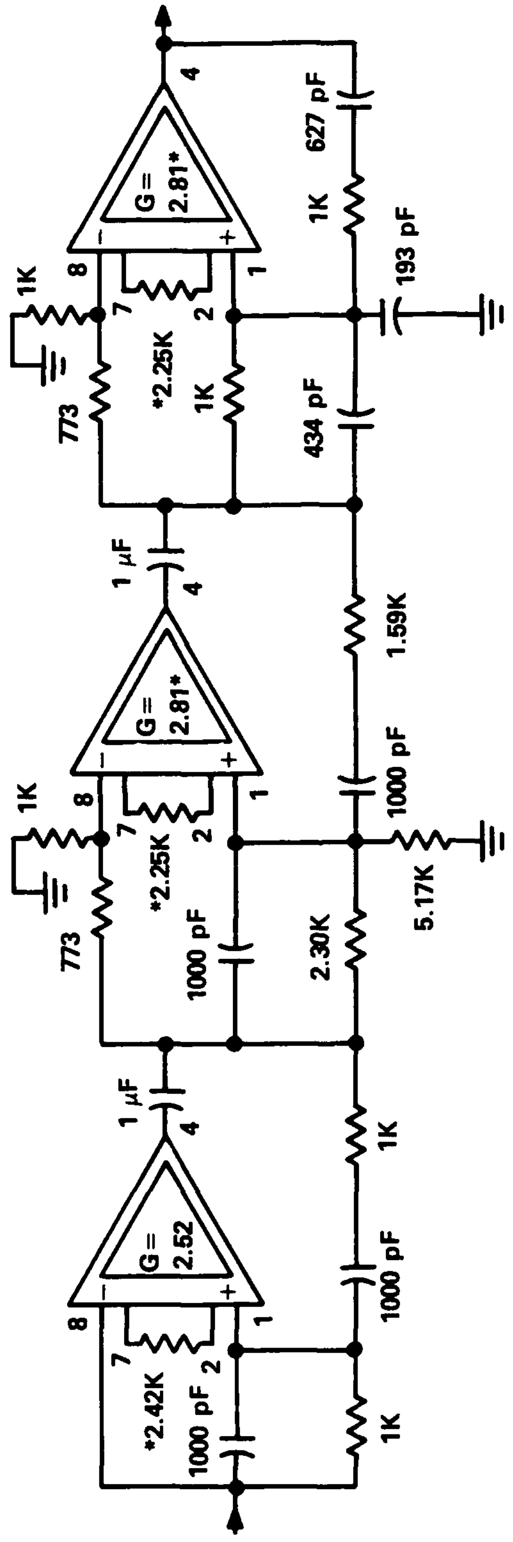


FIGURE 26. ELLIPTIC BANDPASS USING OP-AMPS



NOTES:
1. AMPLIFIERS: TL592
*NOMINAL VALUE; ADJUSTED

FIGURE 27. ELLIPTIC BANDPASS USING FGAS

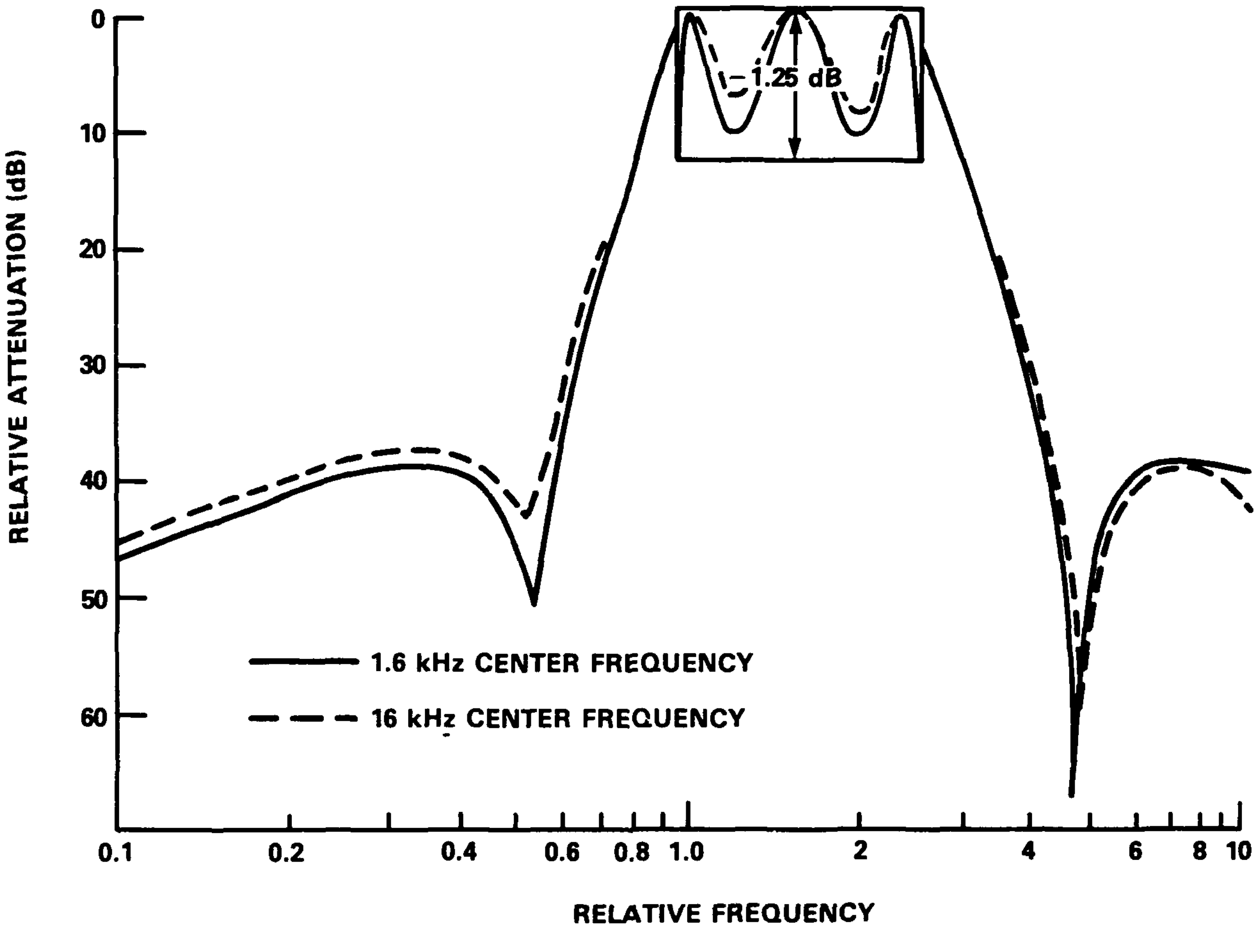


FIGURE 28. PERFORMANCE OF ELLIPTIC BANDPASS USING OP-AMPS

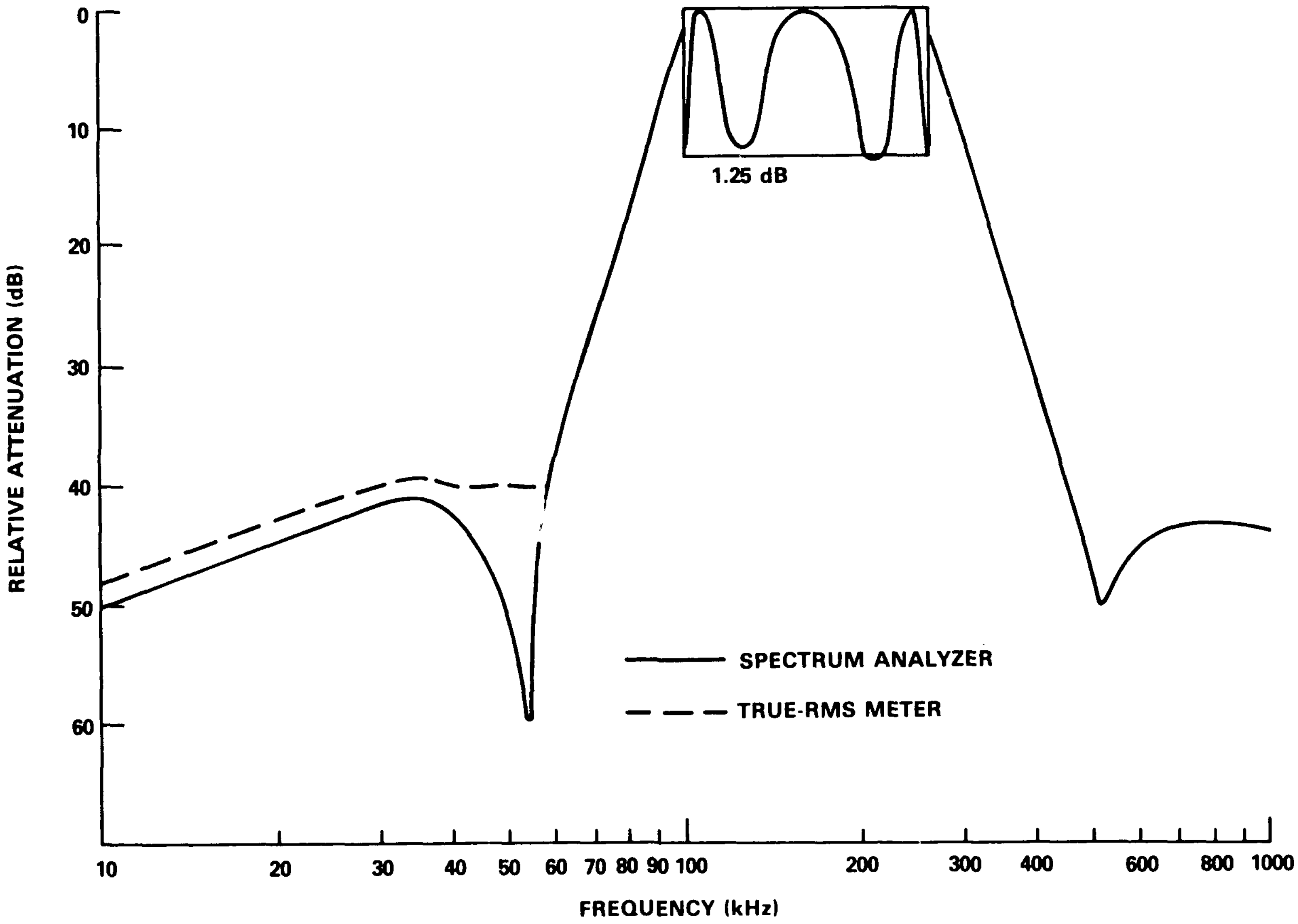


FIGURE 29. PERFORMANCE OF ELLIPTIC BANDPASS USING FGAS

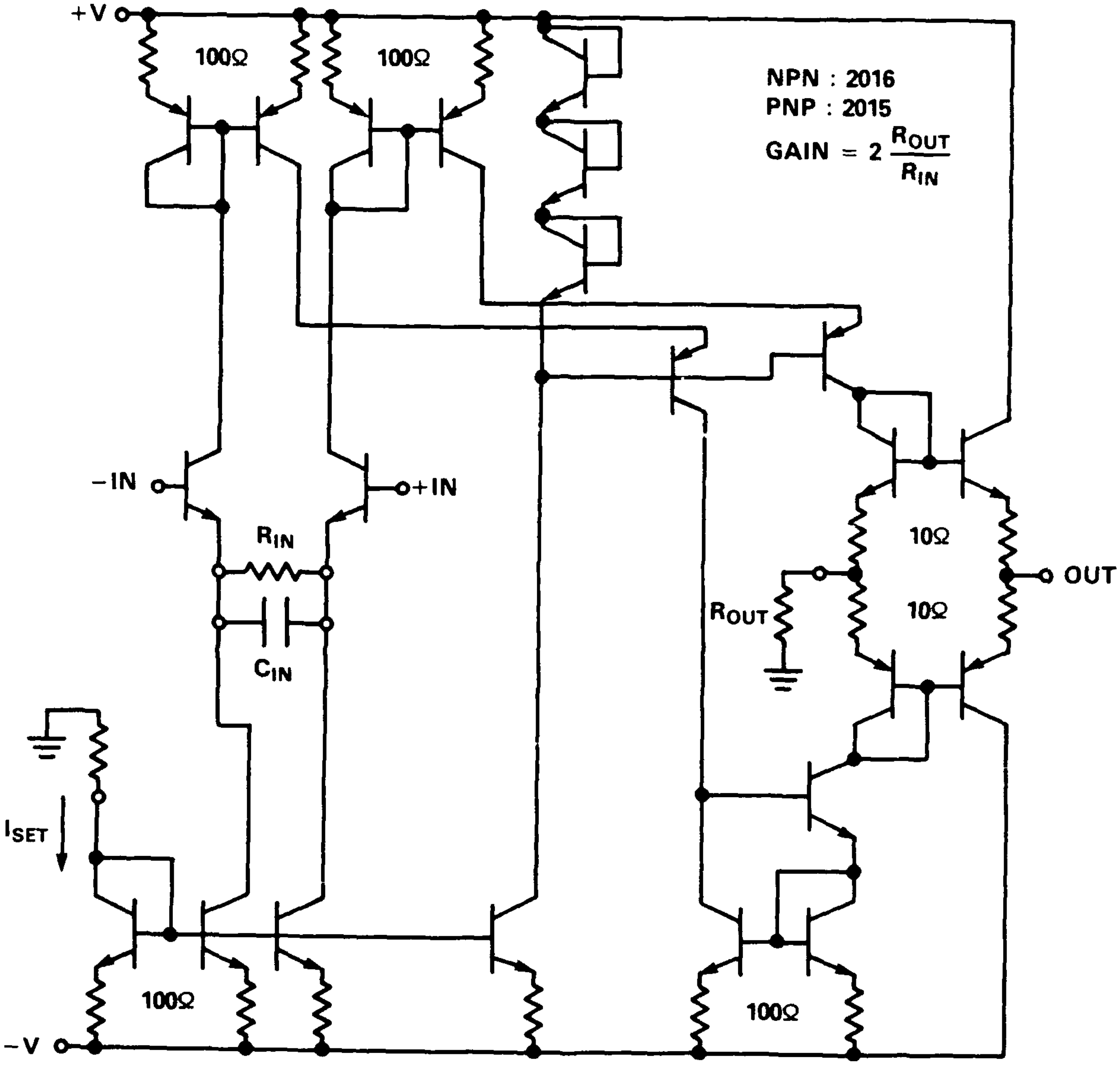


FIGURE 30. FGA INTERNAL CIRCUIT

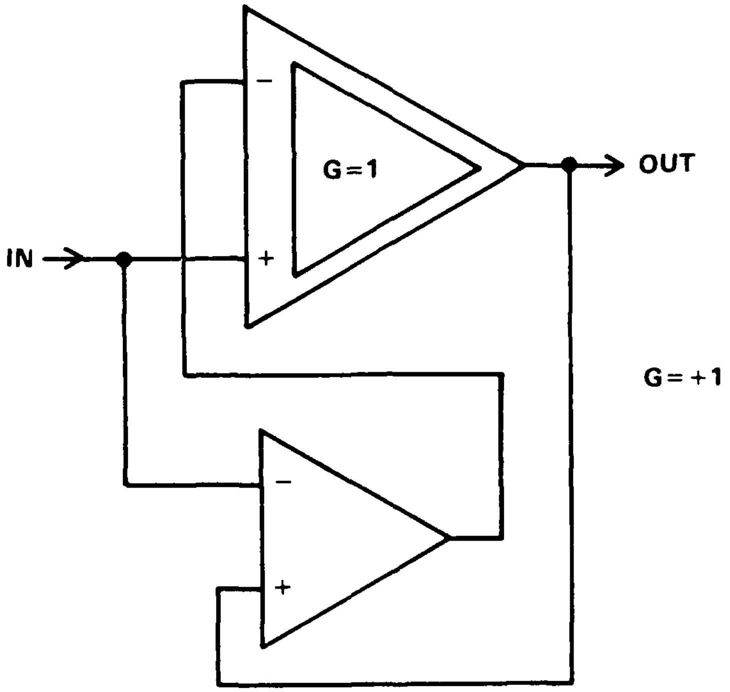
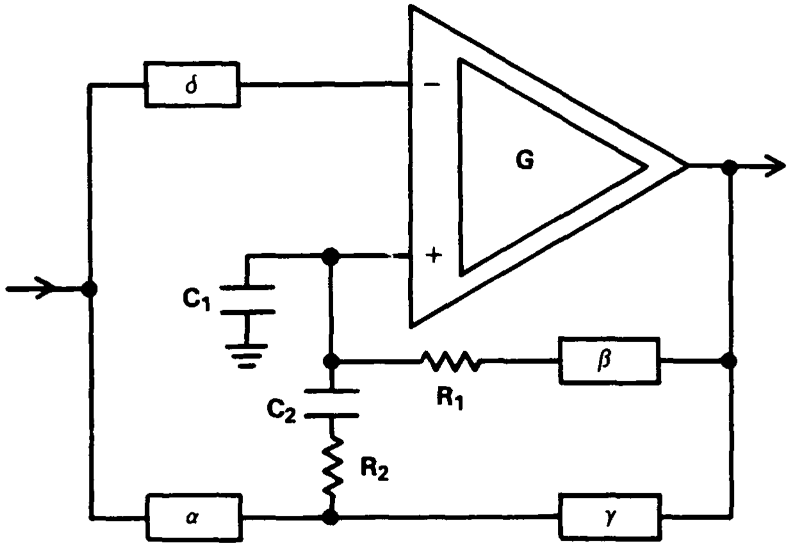
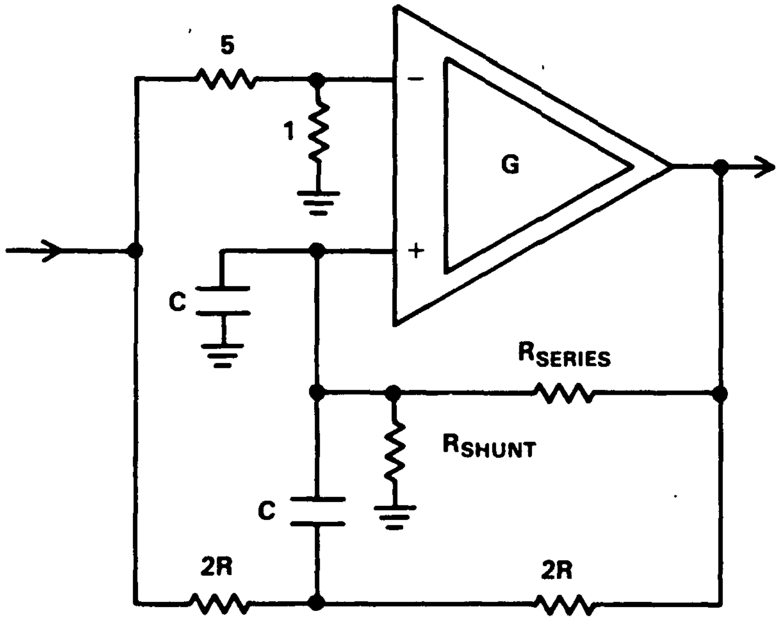


FIGURE 31. COMPOUND AMPLIFIER



$$\frac{\ell_{OUT}}{\ell_{IN}} = -\delta G \frac{S^2+\left[\frac{1}{R_1C_1}+\frac{1}{R_2C_2}+\frac{(1-\alpha/\delta)}{R_2C_1}\right]S+\frac{1}{R_1R_2C_1C_2}}{S^2+\left[\frac{(1-G\beta)}{R_1C_1}+\frac{1}{R_2C_2}+\frac{(1-G\gamma)}{R_2C_1}\right]S+\frac{(1-G\beta)}{R_1R_2C_1C_2}}$$



NOTES:

$$\frac{1}{R_{SERIES}}+\frac{1}{R_{SHUNT}}=\frac{1}{R}$$

$$\frac{R_{SHUNT}}{R_{SHUNT}+R_{SERIES}}=\beta$$

$$\frac{\ell_{OUT}}{\ell_{IN}} = -\frac{G}{6}\,\frac{S^2+\frac{1}{R^2C^2}}{S^2+\left[\frac{3-G\beta-G/2}{RC}\right]S+\left[\frac{1-G\beta}{R^2C^2}\right]}$$

FIGURE 32. LOW-PASS FILTER SECTION, EQUAL CAPACITORS

TABLE 1. COMPONENT VALUES, OP-AMP RESONATOR WITH ZEROS

HIGHPASS	LOWPASS
$\beta = 1; C_1 = C_2 = 1$	$\alpha = 1; R_1 = R_2 = 1$
$R_1 = \frac{\left(1-\frac{D}{B}\right)}{A}$	$C_2 = \frac{\left(1-\frac{B}{B}\right)}{A}$
$R_2 = \frac{1}{BR_1}$	$C_1 = \frac{1}{BC_2}$
$G = \frac{\left(R_1+R_2-\frac{A}{B}\right)}{R_1}$	$G = \frac{\left(C_1+C_2-\frac{A}{B}\right)}{C_1}$
$\alpha = \frac{G+\frac{D}{B}}{G+1}$	$\beta = \frac{G+\frac{B}{D}}{G+1}$
$R_{SERIES} = \frac{R_1}{\alpha}$	$C_{SERIES} = \beta C_1$
$R_{SHUNT} = \frac{R_1}{(1-\alpha)}$	$R_{SHUNT} = (1-\beta)C_1$

NOTE:

$$H(s) = K\frac{S^2+D}{S^2+AS+B}$$

TABLE 2. COMPONENT VALUES, FGA RESONATOR WITH ZEROS

FILTER FUNCTION	FORMULA	δ	G	R_{SER}	R_2	R_{SHU}	C_{SER}	C_2	C_{SHU}
POLE-ZERO QUAD, LOWPASS WITH IMAGINARY ZEROS	$\frac{s^2+D}{s^2+As+B}$ D>B	$1-\frac{1}{2+B/D}$	$3-\frac{A}{\sqrt{B}}$	1	1	NONE	$\frac{1}{\sqrt{B}}(2-\frac{3}{2+B/D})$	$\frac{1}{\sqrt{B}}$	$\frac{1}{\sqrt{B}}(\frac{3}{2+B/D}-1)$
POLE-ZERO QUAD HIGHPASS WITH IMAGINARY ZEROS	$\frac{s^2+D}{s^2+As+B}$ D<B	$1-\frac{1}{2+D/B}$	$3-\frac{A}{\sqrt{B}}$	$\frac{1/\sqrt{B}}{2-\frac{3}{2+D/B}}$	$\frac{1}{\sqrt{B}}$	$\frac{1/\sqrt{B}}{\frac{3}{2+D/B}-1}$	1	1	NONE
POLE-ZERO QUAD, NOTCH	$\frac{S^2+B}{s^2+As+B}$	2/3	$3-\frac{A}{\sqrt{B}}$	$\frac{1}{\sqrt{B}}$	$\frac{1}{\sqrt{B}}$	NONE	1	1	NONE
POLE-ZERO QUAD, ALLPASS	$\frac{s^2-As+B}{s^2+As+B}$	$1-\frac{1}{3+A/\sqrt{B}}$	$3-\frac{A}{\sqrt{B}}$	$\frac{1}{\sqrt{B}}$	$\frac{1}{\sqrt{B}}$	NONE	1	1	NONE
POLE-PAIR SINGLE-ZERO, BANDPASS	$\frac{s}{s^2+As+B}$	1	$3-\frac{A}{\sqrt{B}}$	$\frac{1}{\sqrt{B}}$	$\frac{1}{\sqrt{B}}$	NONE	1	1	NONE
POLE-ZERO PAIR, ALLPASS	$\frac{s-1}{s+1}$	1/2	DOESN'T MATTER	1	NONE	NONE	NONE	NONE	1

TABLE 3. SAMPLE FGA SPECIFICATIONS

SPECIFICATION	NPN IN	PNP IN	UNITS
GAIN ERROR (NO LOAD)	−1.0	+1.5	%
OFFSET VOLTAGE	46	40	mV
INPUT CURRENT	11	−9.5	μA
INPUT RESISTANCE	1.8	1.4	MΩ
INPUT CAPACITANCE	6	7	pF
C.M. RANGE	±13	±14	V
OUTPUT IMP	29	29	Ω
SIGNAL RANGE	±13	±13	V
C.M.R.R.	42	42	dB
+P.S.R.R.	31	30	dB
−P.S.R.R.	30	32	dB
S.S.3dB BW	>50*	>50*	MHz
POWER BW (±5V)	4	4	MHz
TRANSITION TIME, + STEP IN	5*	14	nSEC
TRANSITION TIME, − STEP IN	14	6*	nSEC
SLEW RATE, + STEP IN	320*	110	V/μSEC
SLEW RATE, − STEP IN	110	260*	V/μSEC
DISTORTION, 30 kHz	0.04	0.04	%
MINIMUM SUPPLY	±3.2	±3.3	V
SUPPLY CURRENT	18	19	mA

*MEASUREMENT LIMITED BY TEST GENERATOR

TEST CONDITIONS (UNLESS OTHERWISE SPECIFIED)

SUPPLY VOLTAGE = ±15V
R_{IN} = 10K R_{OUT} = 5K C_{IN} = 10 pF
LOAD 1K
I_{SET} = 3MA
SIGNAL TEST FREQUENCY 100 kHz
SIGNAL TEST AMPLITUDE ± 1V PEAK

NOTE: MEASUREMENTS TAKEN AT BOTH INPUTS; WORST SPEC TAKEN

REFERENCES

1. Delagrange, Arthur D. and Douyon, Reynold, "Pocket Calculator Eases Filter Design," EDN, 24 Jan 1985, p. 243.
2. Delagrange, Arthur D., "Build Active Filters Without Op-Amps," EDN, 20 Feb 1986, p. 246.

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