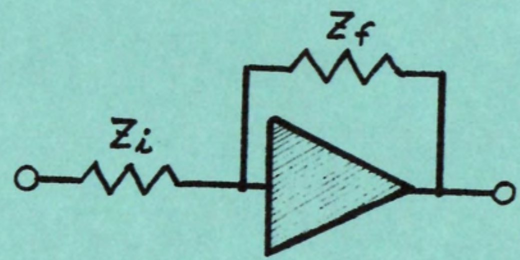
I N S T R U M E N T   E N G I N E E R I N G

TEKTRONIX, INC.

NOTES ON OPERATIONAL AMPLIFIER

Applications



Hiro Moriyasu

January, 1962

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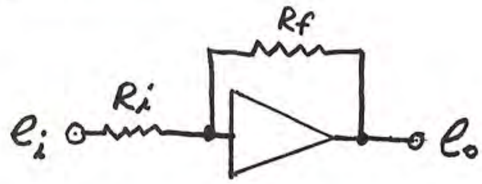
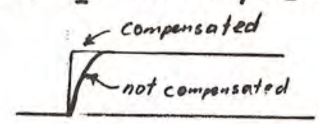
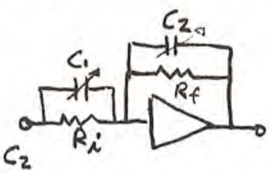
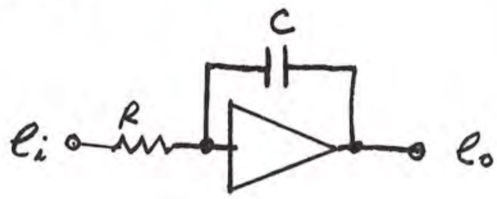
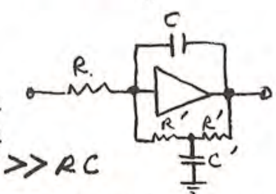
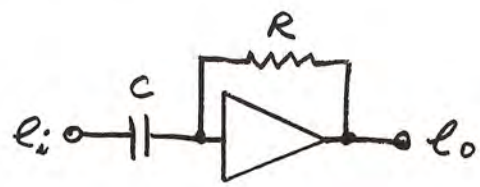
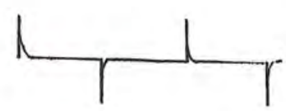
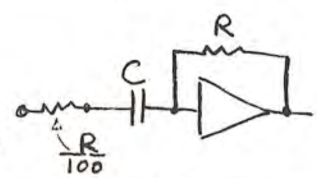
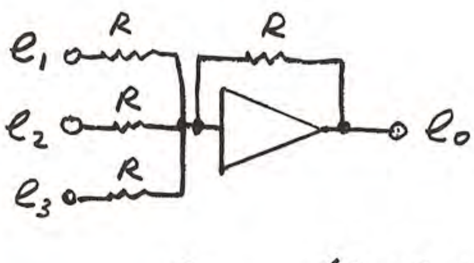
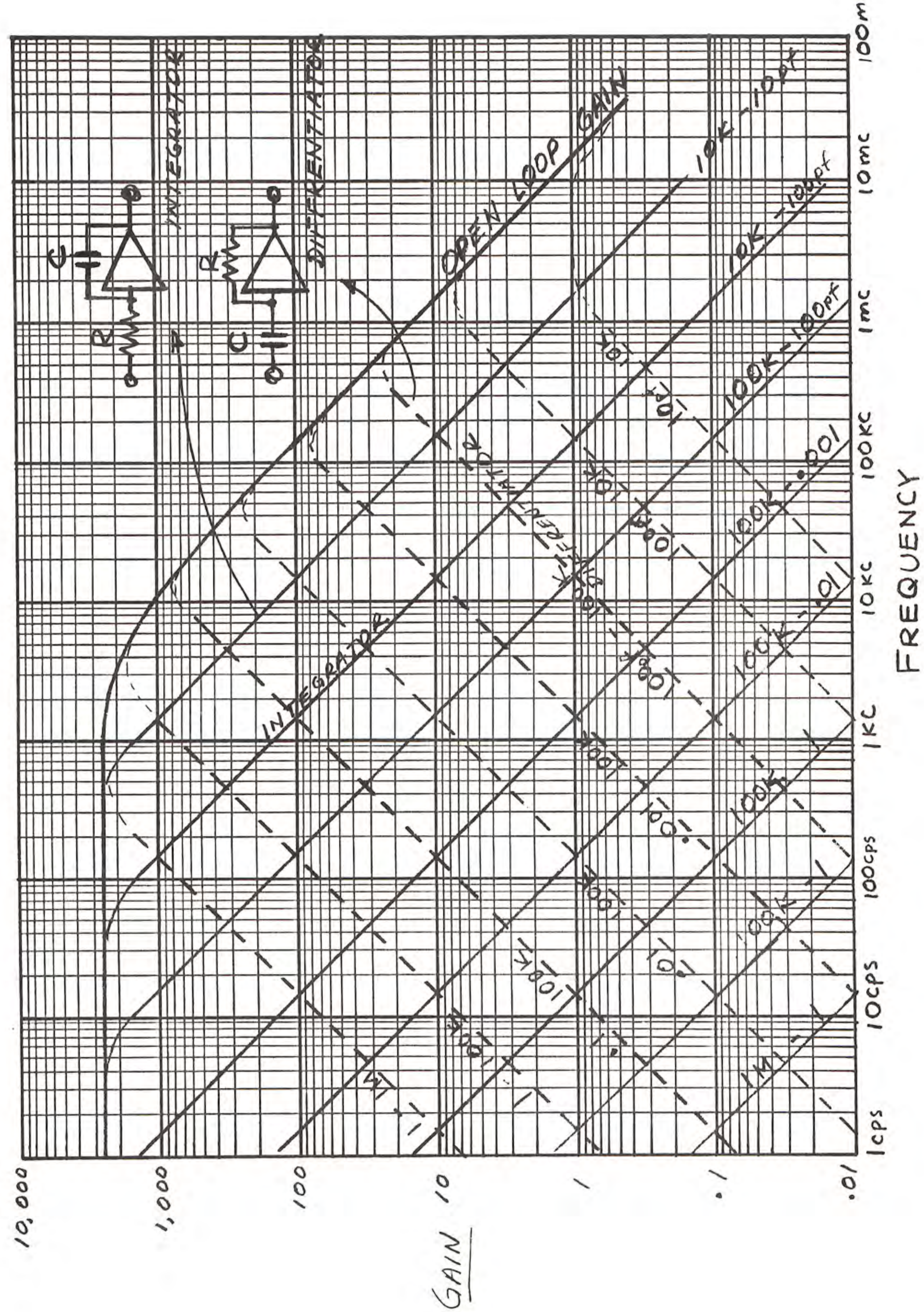
H.Moriyasu
June 1961

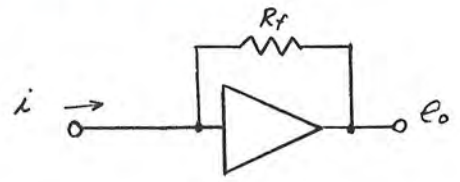
BASIC OPERATIONS	CHARACTERISTICS
Amplification  $e_o = -\frac{R_f}{R_i} e_i$	Gain of the amplifier is determined by the ratio of R_f to R_i. note the negative sign. Step function response  High frequency compensation  $R_i C_1 = R_f C_2$
Integration  $e_o = -\frac{1}{RC}\int e_i \, dt$	Gain $= -\frac{1}{RC\,2\pi f}$ Square wave response  Drift compensation for ac integration  $R'C' >> RC$
Differentiation  $e_o = -RC\frac{de_i}{dt}$	Gain $= -RC\,2\pi f$ Square wave response  H.F. noise suppression for L.F. differentiation 
Summation  $e_o = -(e_1 + e_2 + e_3)$	Gain of this summing amplifier is one. Higher gain can be obtained by increasing the feedback resistor just the same way as the amplifier. Here again output sign is negative.

Rivisions


INTEGRATOR
DIFFERENTIATOR
OPEN LOOP GAIN
R
C
10K-10pf
10K-100pf
100K-100pf
100K-.001
100K-.01
100K
1cps
10cps
100cps
1KC
10KC
100KC
1mc
10mc
100mc
FREQUENCY
10,000
1,000
100
10
1
.1
.01
GAIN

VOLTAGE - CURRENT CONVERSIONS

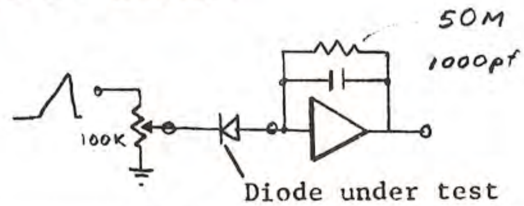
Current to voltage



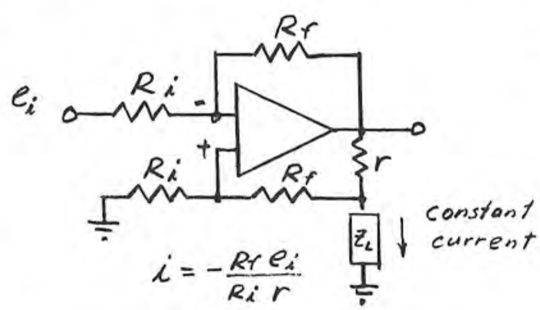
$$e_o = -iR_f$$

Very low current measurement application. The output voltage is proportional to the input current. For example $R_f = 1$ meg give 1 volt/ua.

Typical application: diode leakage test to 1 nanoamp.



Voltage to current

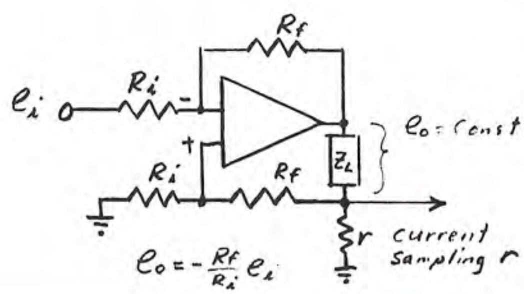


Positive feedback to grid maintains voltage across r constant. If R_f and R_i are made much higher than load impedance, almost all the current flows into the load.

Then $$i = \frac{-R_f e_i}{R_i r}$$

If $$Z_L << R_f + R_i$$

Voltage to voltage

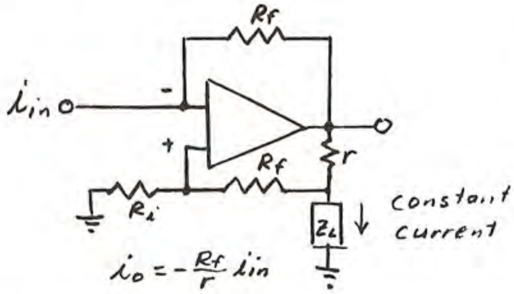


Amplifier maintains constant voltage across the load, while allowing insertion of current sampling resistor.

This may be used to study nonlinear component testing, using scope sawtooth.

$$e_o = -\frac{R_f}{R_i} e_i$$

Current to current



Current to current amplifier.

The maximum output current is limited by the amplifier capability.

$$i_o = -\frac{R_f}{r} i_{in}$$

if

$$Z_L << R_f + R_i$$

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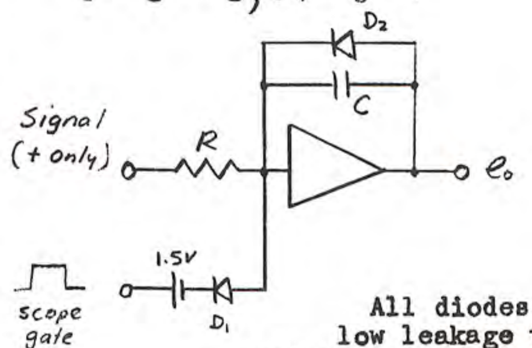
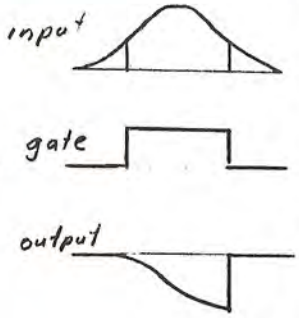
GATED INTEGRATOR

Simple gating, (+) signal

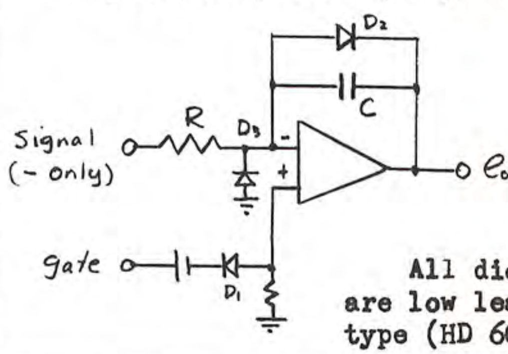


All diodes are low leakage type such as (HD 6045)

Gating integrator accepts positive signals only.
When gate is zero output is clamped by D_z to approx. +0.5V



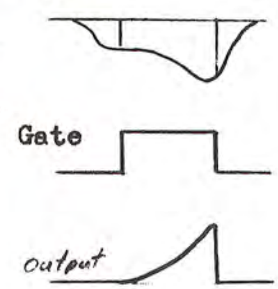
Simple gating for (-) signal



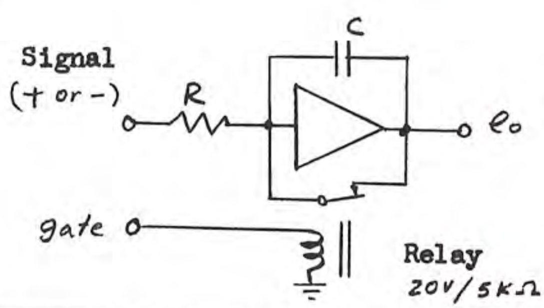
All diodes are low leakage type (HD 6045)

Negative signal can be gated by rearranging the circuit. The gate will drive grid.

When gate is zero output is clamped to approx. − 0.5 V

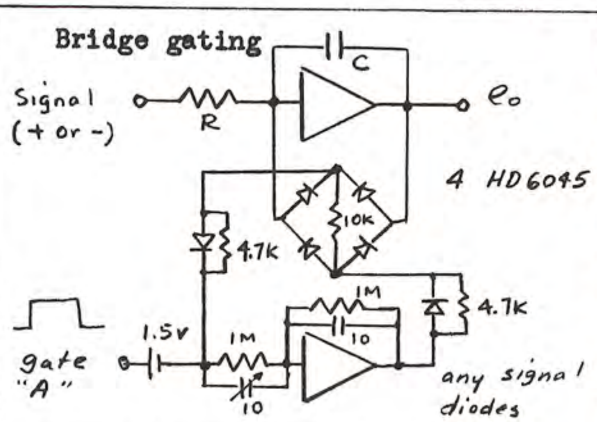


Relay gating for low speed

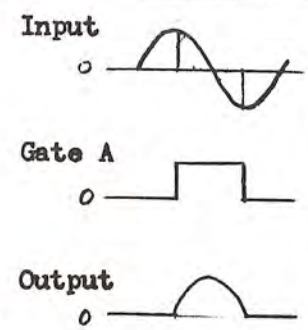


For very slow speed application, relay can serve simple gating.
Input can be + or −

Bridge gating



This arrangement uses diode bridge and gating amplifier B. It can accept + or − input signal.
Output signal should not exceed the gating voltage. Using 535,45,"A" gate, any portion of curve may be integrated.



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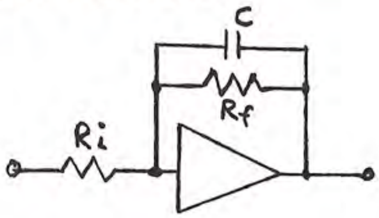
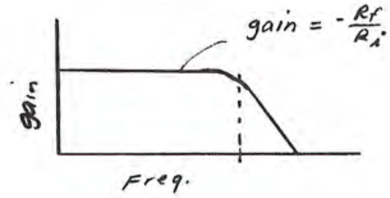
BANDPASS AMPLIFIER

Low pass amplifier



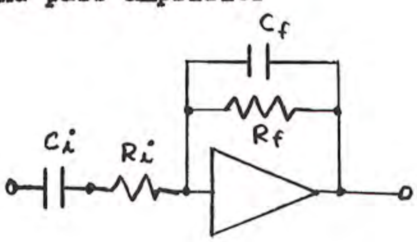
$$Gain = -\frac{R_f}{R_i}$$



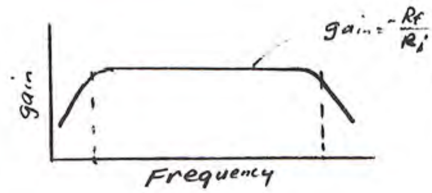
High Freq. response

$$f_{H.F.} = \frac{1}{2\pi R_f C_f} \text{ cps}$$

Band pass amplifier



$$Gain = -\frac{R_f}{R_i}$$



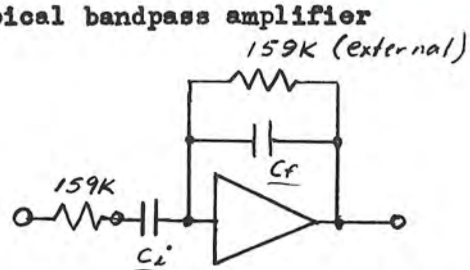
L.F. response

$$f_{L.F} = \frac{1}{2\pi R_i C_i} \text{ cps}$$

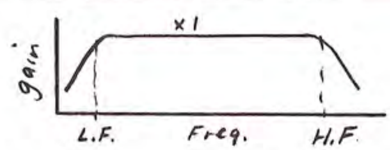
H.F response

$$f_{H.F} = \frac{1}{2\pi R_f C_f} \text{ cps}$$

Typical bandpass amplifier

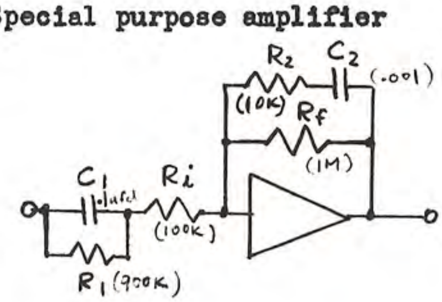


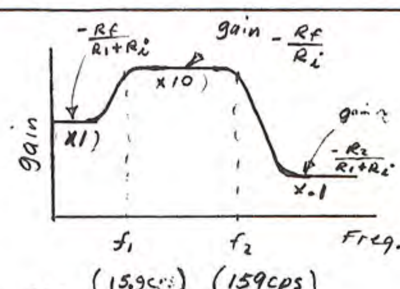
$\underline{C_i}$ and $\underline{C_f}$ selected by switch 10pf - 1ufd



L.F.	Ci	H.F.	Cf
1cps	1ufd	100KC	10pf
10c	.1	10KC	.0001ufd
100c	.01	1KC	.001
1KC	.001	100c	.01
10 KC	.0001	10c	.1
100kc	10pf	1c	1ufd

Special purpose amplifier



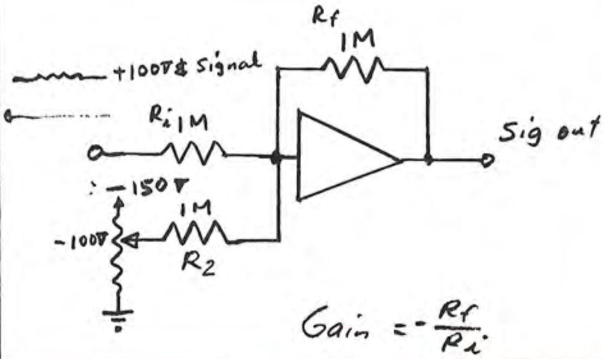


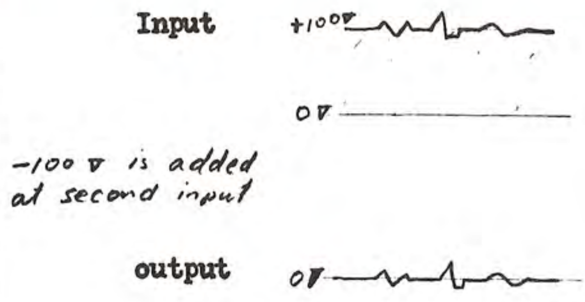
$$f_1 = \frac{1}{2\pi R_i C_1} \text{ cps}$$

$$f_2 = \frac{1}{2\pi R_f C_2} \text{ cps}$$

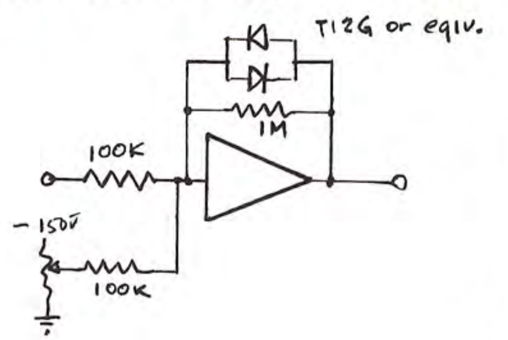
DC MEASURMENTS

DC slideback

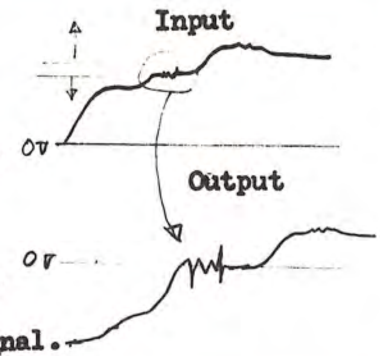




DC slideback with large sig. compression

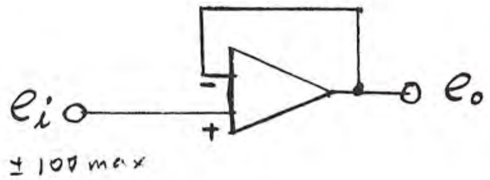


DC slideback can allow to observe small signal superimposed on DC signal.
additional diodes in feedback compress off-screen signal.



HIGH INPUT IMPEDANCE AMPLIFIER

Unity Gain Follower Amplifier



$$e_o = e_i$$

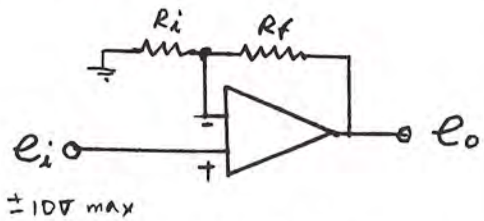
Input grid current is very low, typicallyless than .3 namp thus equivalant imput impedance may be expressed

$$R = \frac{e}{i}$$

For 1 volt input voltage

$$R = \frac{1\ v}{3 \times 10^{-10}} = 3.3 \text{ kmeg}_{equiv}$$

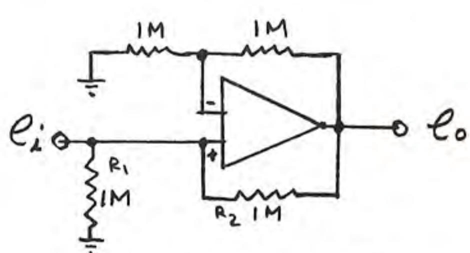
Non-inverting amplifier



$$e_o = \frac{R_i + R_f}{R_i} e_i$$

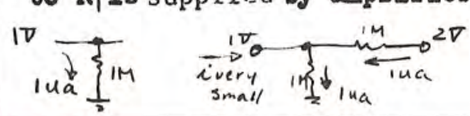
This arrangement offer high input impedance with some gain. output is not phase inverted.

High Input Impedance Amplifier



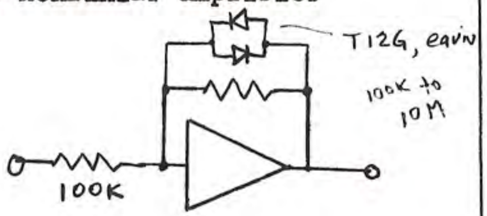
$$e_o = 2 e_2$$

Using positive feedback to input, the input 1 meg resistor may be made to have very high effective resistance. For example, if we apply 1 v to R_1 current of 1 ua flow. since amplifier have gain of 2, the output voltage is 2volts. This results current feedback(+) from output to input so that current into R_1 is supplied by amplifier.

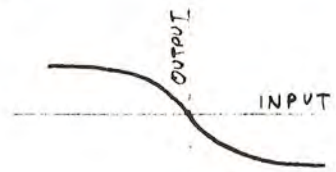


NONLINEAR AMPLIFIER (diode)

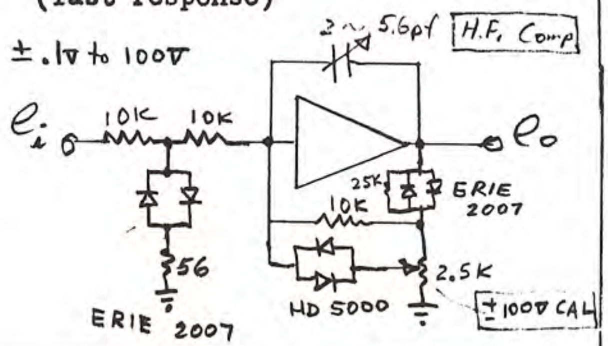
Simple nonlinear amplifier



If diodes are placed in the feedback circuit, this amplifier acts as comppession type amplifier.

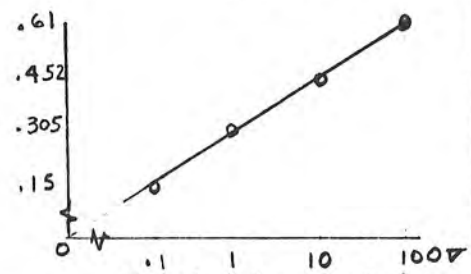


Logarithmic type amplifier (fast response)



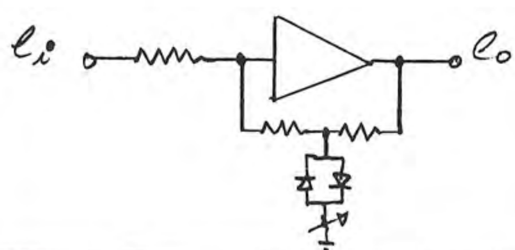
$e_o \approx .305 + .15 \log_{10} e_i$

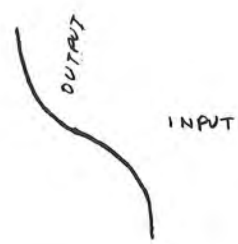
Output

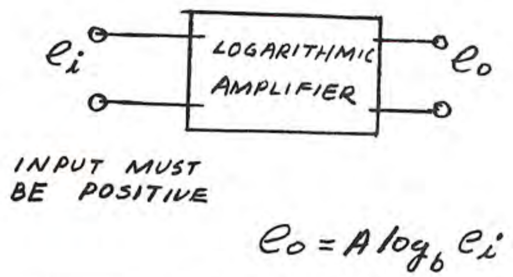
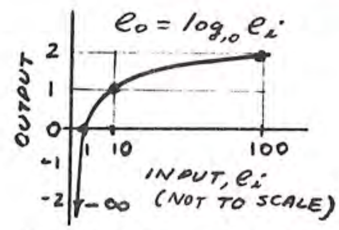
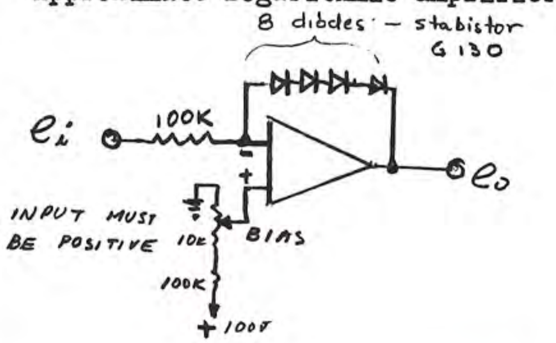
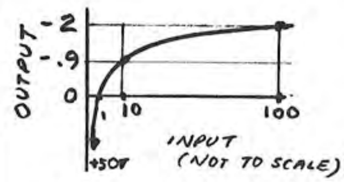
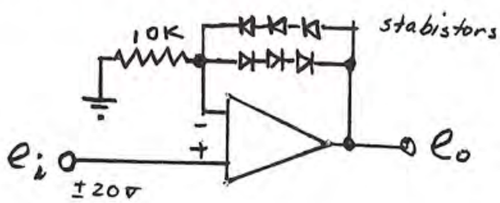
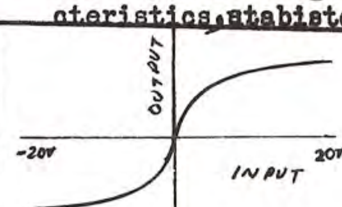
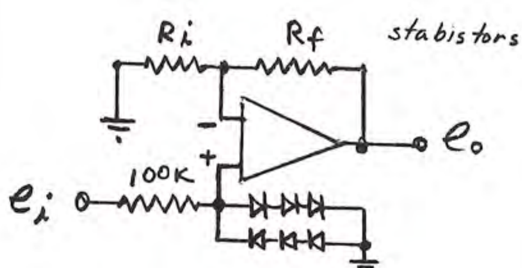
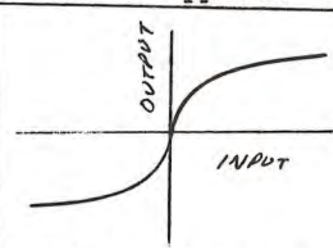


Input (log scale)

Expansion **amplifier**



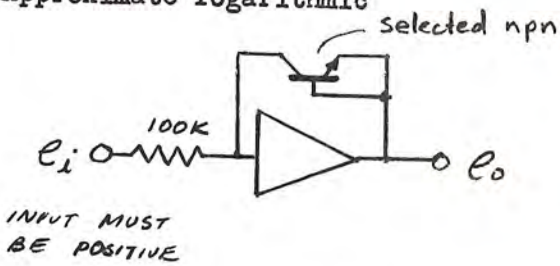


NONLINEAR AMPLIFIERS (log. diode)	CHARACTERISTICS
Theoretical logarithmic amplifier 	 An advantage of true log amplifier is capability of accepting wide range of input signal level, Since input can not be negative value, for ac measurment symmetrical amplifier is recomended.
Approximate logarithmic amplifier 	 Simulating true log amplifier. Bias is adjusted to give zero volt when input is 1-v. when input is zero amplifier saturates to ≈50volts. Many germanium diodes can be used such as T 12G. for more dynamic range & controlled characteristics, stabistors are recomended.
Symmetrical nonlinear amplifier 	 Input is limited to 20v, but it will offer high input impedance. Since this amplifier have back to back diode in the feedback, both signal can be applied. low level application
Symmetrical nonlinear amplifier 	 This amplifier also gives symmetrical output responce with approximate logarithmic compression. For given signal level R_i & R_f may be adjusted for satisfactory out put level.

For temperature stability place diodes in a temperature controlled oven.

<table>
<tr><th>NONLINEAR AMPLIFIERS (transistor)</th><th>CHARACTERISTICS</th></tr>
<tr><td>

Approximate logarithmic



$e_o \approx -A \log_b e_i$

</td><td>

Certain NPN transistor exhibit logarithmic voltage current breakdown characteristics in reverse direction.
This arrangement can accept only positive input signal.

Selection of npn transistor may make this type of logarithmic amplifier impractical since use of certain type diodes can give more predictable logarithmic characteristics.
(only advantage is high level output)

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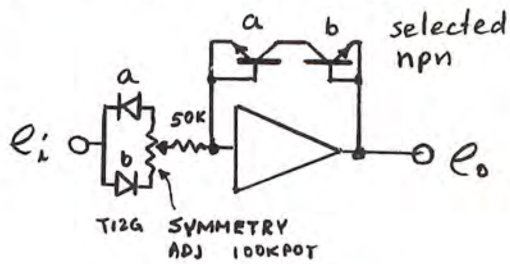
Symmetrical nonlinear amplifier



$e_o \approx -A \log_b |e_i|$

</td><td>

To accept positive and negative signal two transistors (matched) are used.
Limitations are same as listed above.

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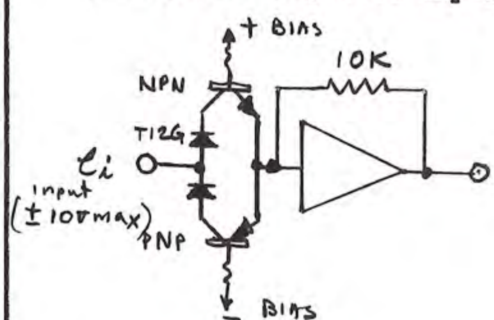
<tr><td>

Symmetrical compressed amplifier



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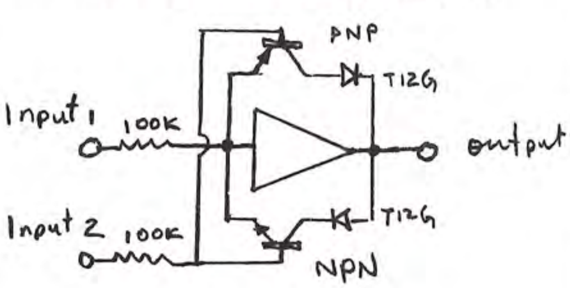
<tr><td>

Possible nonlinearity control



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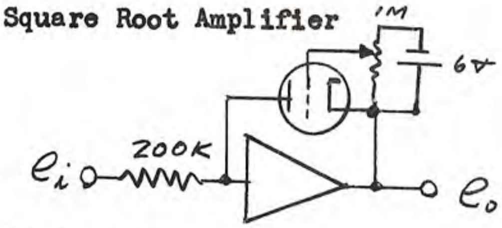
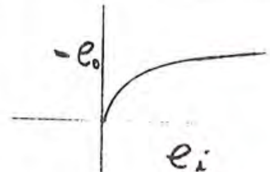
NONLINEAR AMPLIFIER (triodes)

Square Root Amplifier



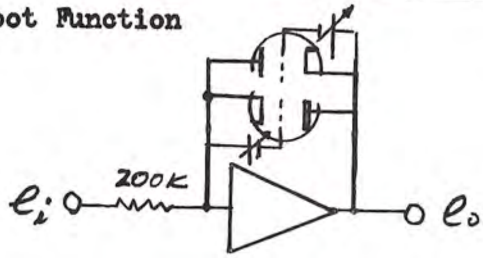
INPUT MUST BE POSITIVE

$$e_o \approx -\sqrt{e_i}$$

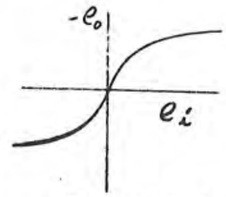


Certain triodes such as 12AU7, muvistor 7586 may be placed in the feedback circuit to obtain square root characteristics.

Root Function

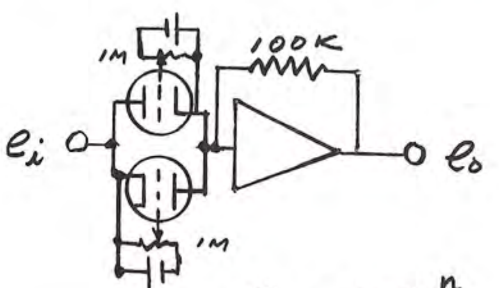


$$e_o = -K|e_i|^{\frac{1}{n}}$$

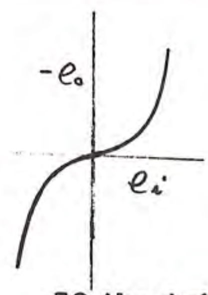


Two triodes placed back to back in the feedback circuit. adjusting bias root may be varied approximatly .9 to 10

Power Function



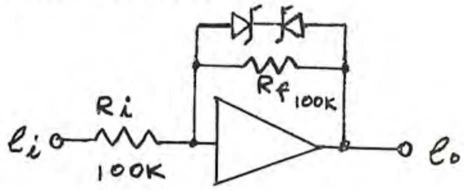
$$e_o = -K e_i^n$$



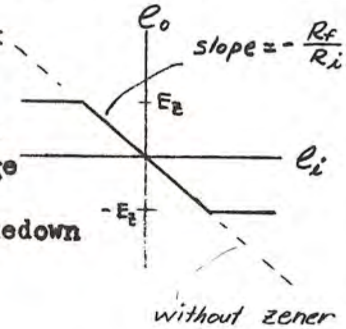
If the triodes are placed in the input circut, power function may be obtained. the power may be varied .9 to 10 approx.

NONLINEAR AMPLIFIERS (zener diodes)

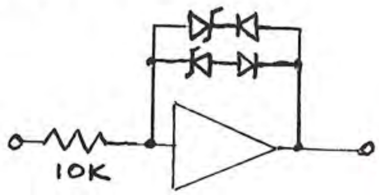
Limiter Amplifier



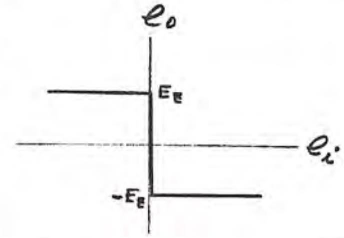
If a back to back zener diode is inserted in the feedback circuit, the output valtage will be limited by the zener brakedown voltage.



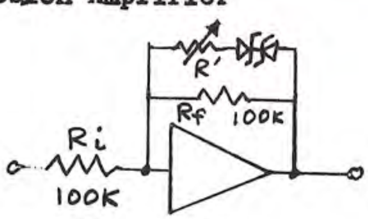
Squaring Amplifier



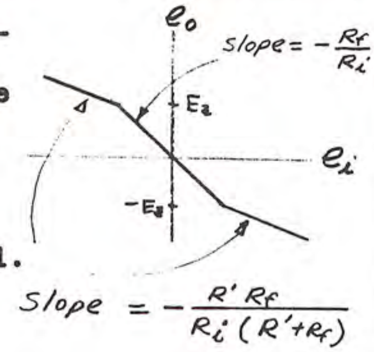
If the feedback resistor in the above amplifier is removed, the amplifier output give very high gain near zero signal. In this arrangement the zener diodes are coupled with low capacity diodes to minimize zener diode capacitance.



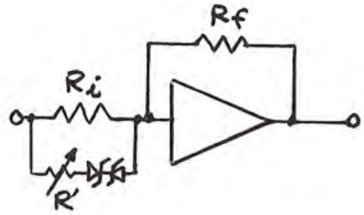
Compression Amplifier



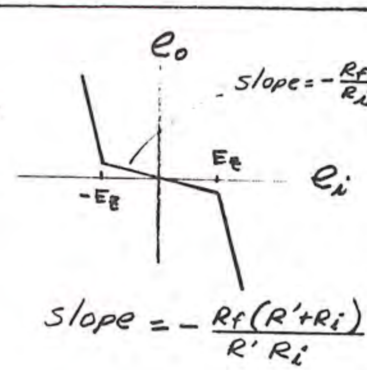
A variable resistor in series with zener diode in the limiter amplifier can control amount of compression for large signal.



Expansion Amplifier



Input output circuit is reversed in this amplifier to obtain higher gain for large signal input



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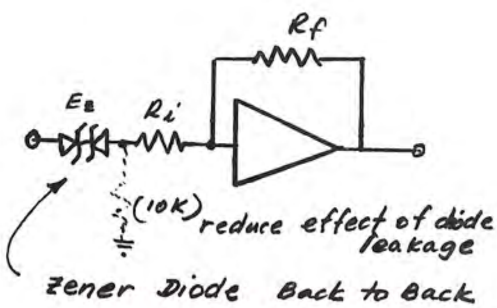
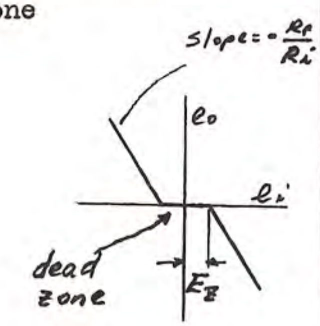
NONLINEAR AMPLIFIERS (**zener diode**) **simulating nonlinear characteristics**

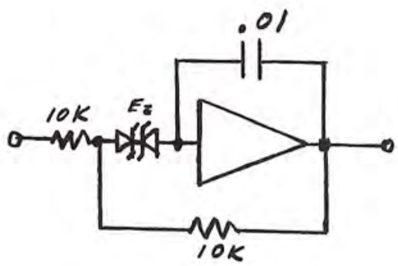
Dead zone



Simulating a dead zone



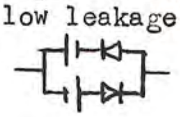
Back-lash

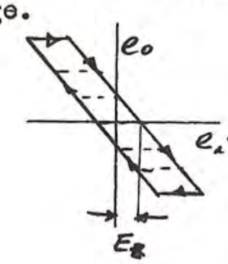


Simulation of backlash;

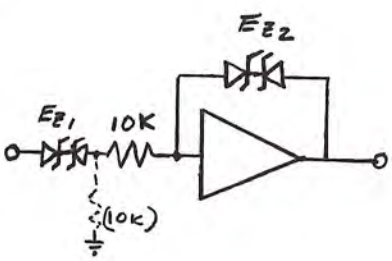
the capacitor hold the voltage and the zener diodeconduct voltage across diode exceed breakedown voltage.

small battery and low leakage diodes may be replaced for zener for low leakage memory.

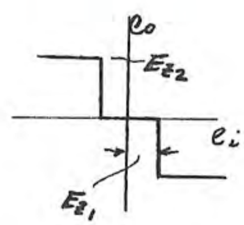




Relay

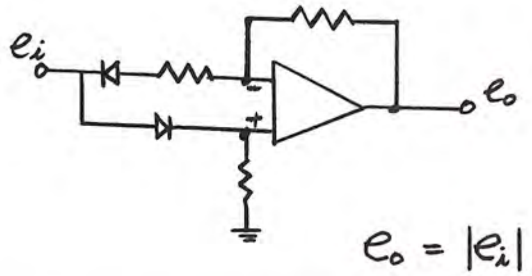


Representation of polarized double throw relay which has equal pull-in and pull-out current

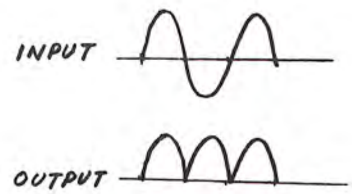


ABSOLUTE VALUE AMPLIFIER

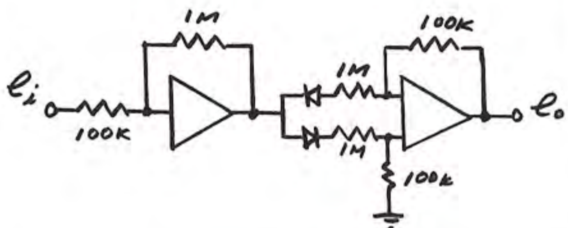
Full-wave rectification



Output gives full-wave rectified wave of input. Output is always positive sign. Diodes contribute ≈ .3 voltage drop.

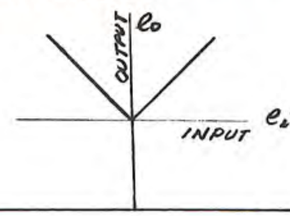


Full-wave rectification (low level)



Inserting an amplifier ahead of full-wave rectifier, effect of diode voltage drop is reduced by factor of amplification.

This technique may be applied to low level full-wave rectification.



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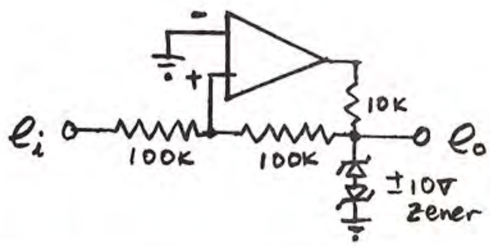
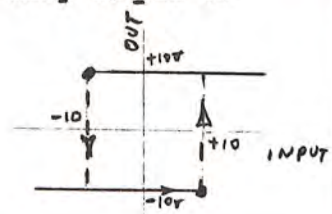
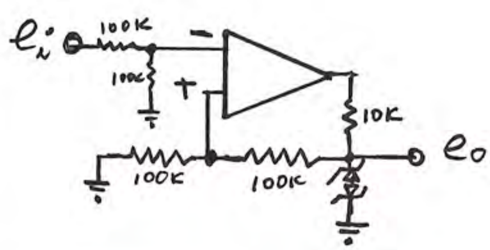
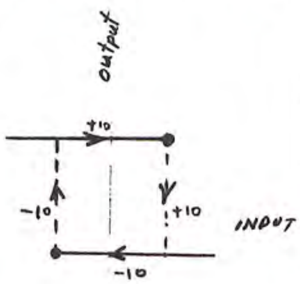
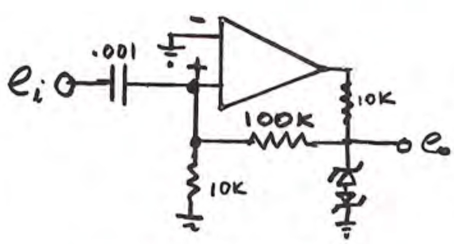
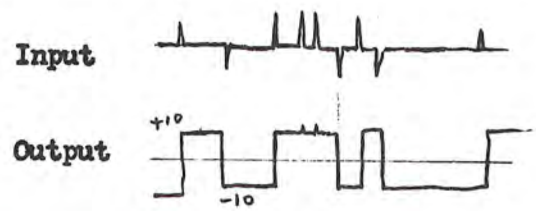
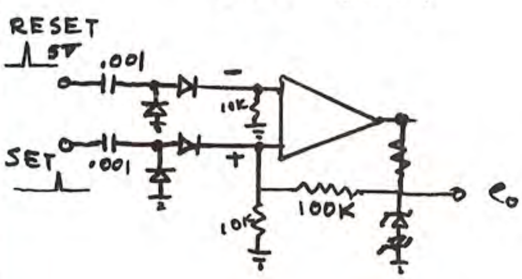
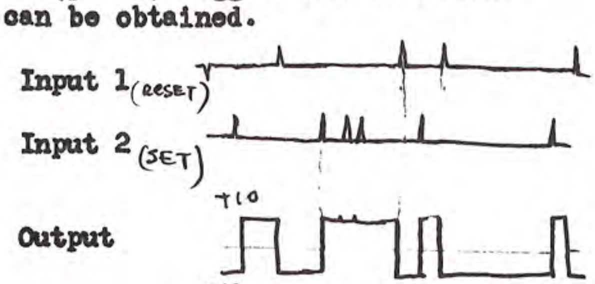
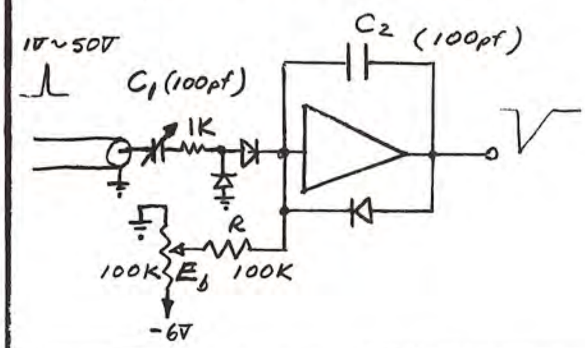
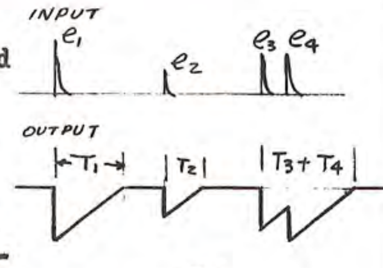
SWITCHING AMPLIFIER (BISTABLE)	CHARACTERISTICS
Bistable Comparator 	Bistable Comparator incorporate a zener diode as a refference, input voltage is compared agaist refference diode; when input voltage become equal to zener voltage output will flip to ±10 v. 
Bistable Comparator 	Similar to above, but output will flip to opposite polarity 
Bistable Multivibrator (single input) 	Out put flip to ±10v anytime opposite polarity pulse arrives. Once flipped additional pulse of same polarity have no effect 
Bistable Multivibrator (two inputs) 	AC (pulse) toggle switch action can be obtained. 

DIGITAL TECHNIQUES

Pulse-Height to Time converter

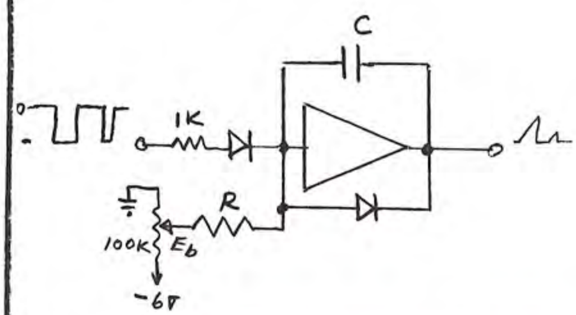


If a positive pulse is applied to the input, it will charge C_1 and this charge is also damped into C_2, causing the output to step down. This voltage is discharged by integrator

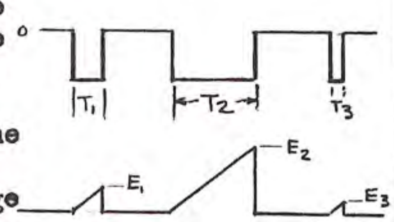


$$T \cong \frac{RC_1}{E_b} e_{pulse}$$

Time to Voltage Converter

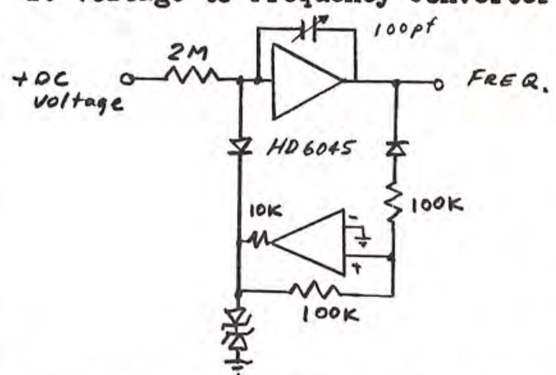


A negative gate opens the diode gate allow the integrator to integrate at the constant rate. The peak voltage is thus proportional to the time(period).



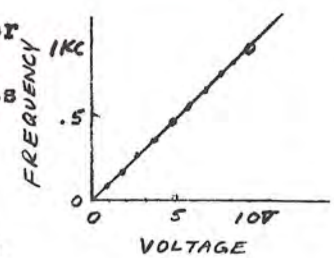
$$E \cong \frac{E_b}{RC} T$$

DC Voltage to Frequency Converter

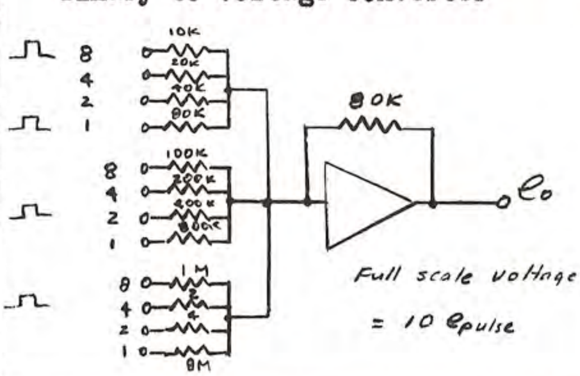


This will give conversion factor of approximatly 1 kc per 10 volts input.

The conversion accuracy is in the neighborhood of ± 1 %.



Binary to voltage converter

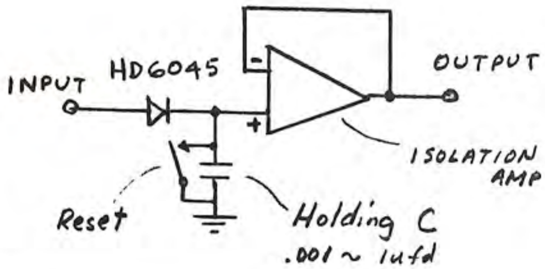


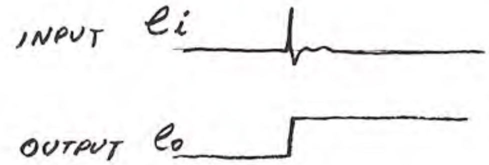
Simple Binary (BCD) to voltage conversion is accomplished by summing input pulse voltages through the properly weiged input resistors.

If input pulse has - 1 volt, the full scale voltage will be 9.99 volts.

PEAK MEMORY AMPLIFIERS

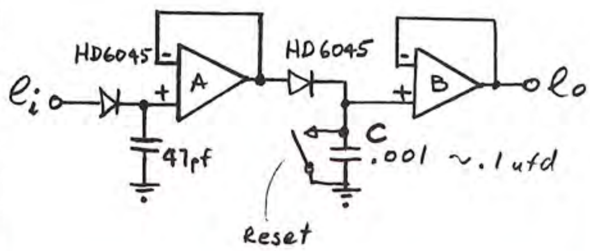
Peak memory amp

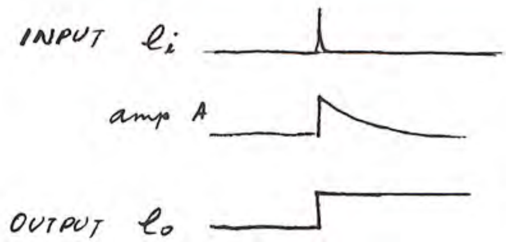




The holding capacitor is charged through low leakage diode, since the leakage of diode (1nanoamp) and grid current (.5namp) are low, voltage can be held

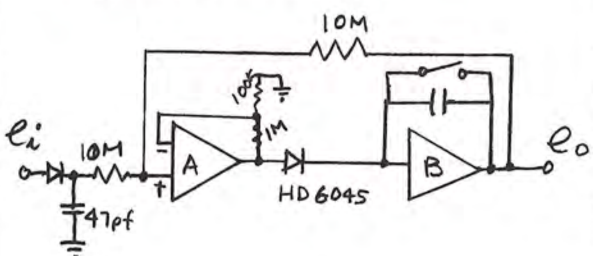
Fast response peak memory amp





To reduce input loading effect, two amplifiers may be cascaded

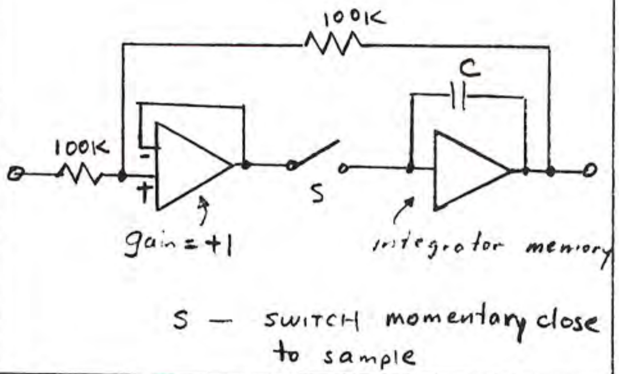
Integrator peak memory



Integrator is used as memory to improve dc accuracy.

SAMPLE-HOLD AMPLIFIER

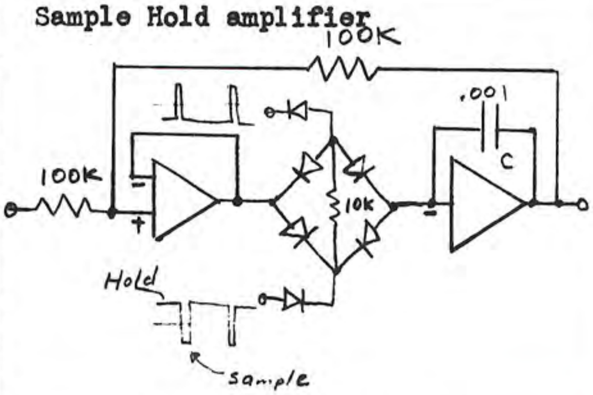
Sample hold

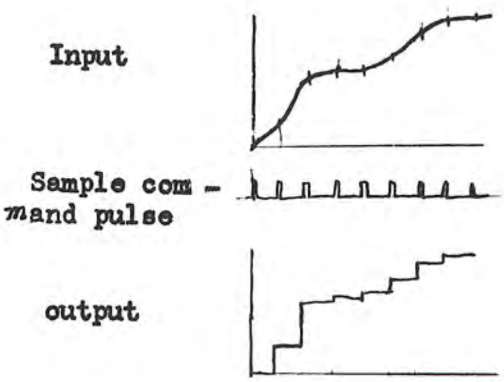


(Illustration of sample hold circuit.)

This circuit is often called __integrator memory__: When the switch is closed the capacitor is charged by the first amplifier. When the switch is open the integrator holds the voltage until the switch is closed again.

Sample Hold amplifier

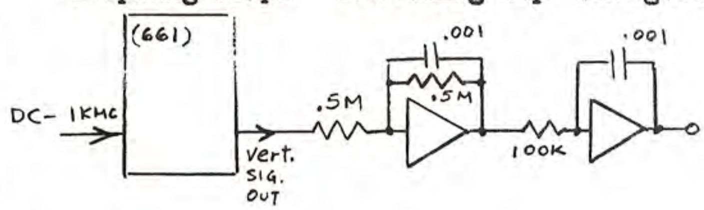




12-6-61 Hm

SAMPLED-DATA

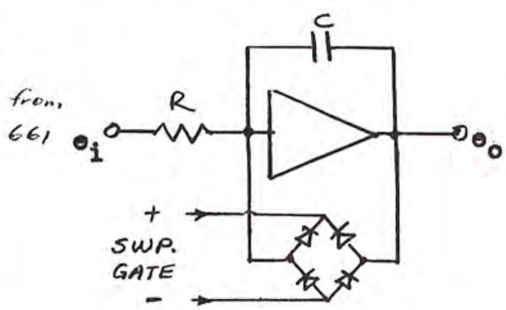
Sampling Integration



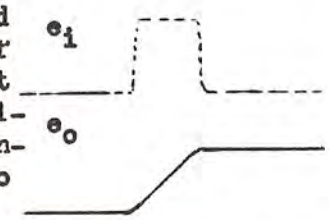
$G(s) \approx \frac{1-e^{-Ts}}{s(T_1 s+1)}$ $\frac{1}{T_2 s+1}$ $\frac{K}{s}$

Sampled-data contain many higher frequency components as well as desired lower frequency signals. In many operation, it may be necessary to insert a smooting amplifier before doing a linear operation. It is possible to integrate repetitive signal to approximatly 1 kmc using sampling scope vertical signal out.

Sampled-pulse Integration

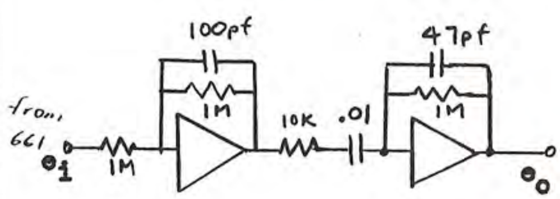


Sampled-pulse may be integrated to obtain area of the pulse in volt sec. Proper scaling factor to convert real time to sampling time is necessary.

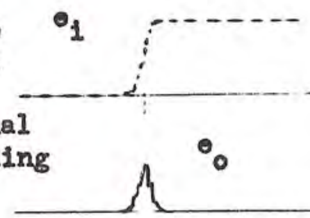


Detail of gating circuit see gated integrator.

Sampled-pulse Differentiation

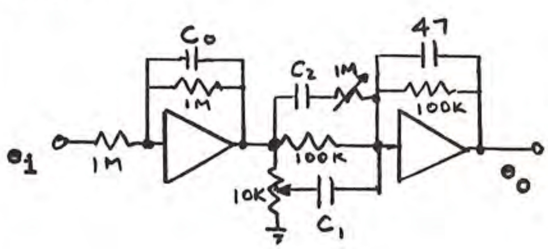


Differentiation of sampled pulse may be performed after passing the sampled signal through a smoothing amplifier.

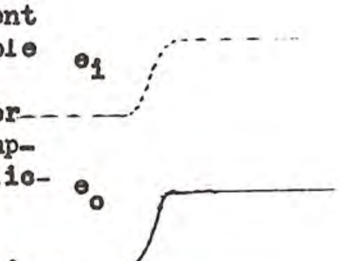


Additional H.F. limiting circuit is necessary in differentiation.

Possible risetime compensation circuit



This arrengement can prvide posible risetime improvement, however this type of compensation is applicable to a given frequency and given sweep speed.



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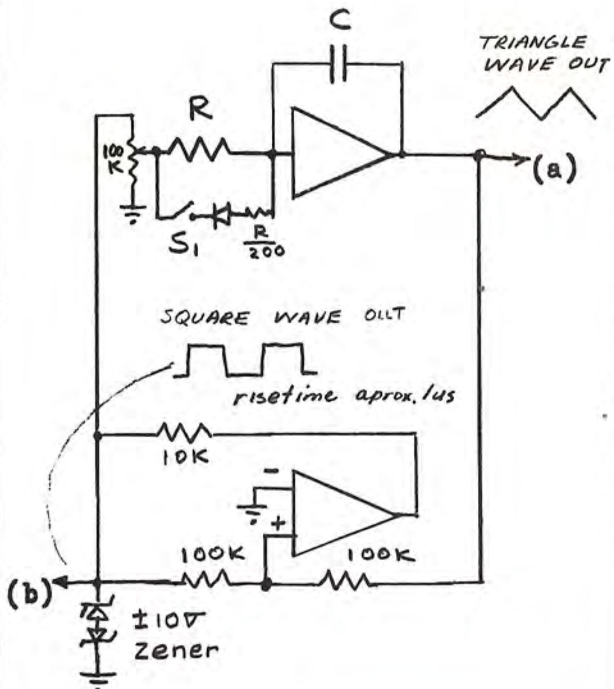
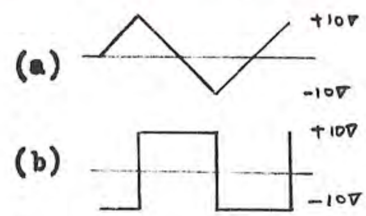
L. F. FUNCTION GENERATORS

Triangle, Square, Sawtooth & Pulse Generator



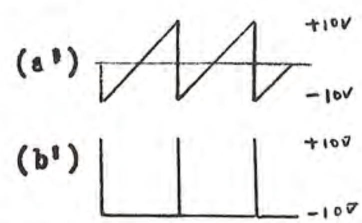
Combining an integrator and a bistable comparator, precise low frequency waveforms can be generated. Operational amplifier B is working as a bistable comparator which switches when input reach + or - 10 volts and output puts out ±10 volts square wave.

Normal waveform at (a) and (b) are



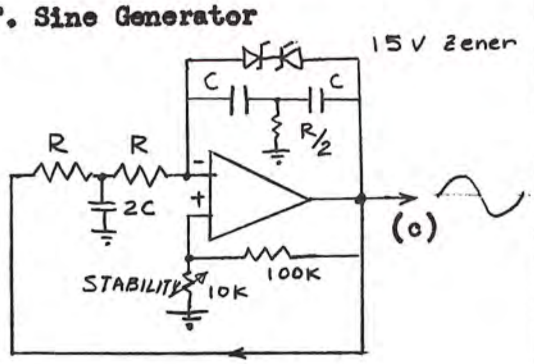
$$f = \frac{1}{4RC}$$

When switch S_1 is closed,



$$f = \frac{1}{2RC}$$

L.F. Sine Generator

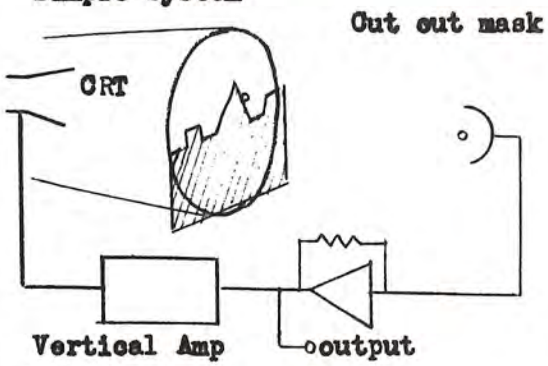


A very low frequency sine wave can be generated with twin T filter network in the feedback loop of a operational amplifier. Positive feedback is provided to sustain oscillation. Amplitude is controlled by a nonlinear impedance of zener diode in the negative feedback.

$$f = \frac{1}{2\pi RC}$$

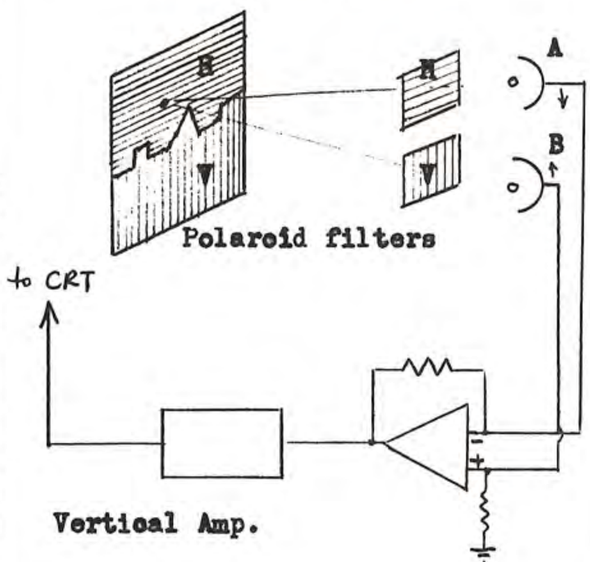
CRT FUNCTION GENERATOR

Simple System



A light sensitive element is placed in-front of the CRT and the mask. If the beam is above the mask, negative signal will be produced to force the beam to move down. Normaly the beam is positioned above the mask so that beam always tries to go up, however, the light feed-back does not allow the beam to show too much. As a result the beam follow the cut out mask. DC coupled signal can be obtained at the output of operational amplifier.

Differential Fast System



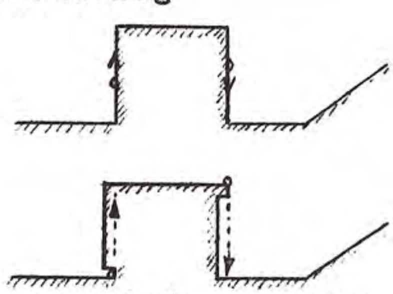
When using the simple system the spot size has to be made small to obtain good resolution, but when it is operated at the low light level it will suffer from speed.

The differential system incorporates polaroid filter masks and two light sensing elements. Substantial improvement in speed and resolution may be expected.

When the beam spot is in H plane the light is sensed by light sensor A. B will not receive light since the filter is out of phase. Thus the signal from A will force the beam to move down. If the beam spot is in V plane it, likewise, will be forced upward by B.

The light is picked up differentially and the beam is moved push-pull action.

Mask Cutting



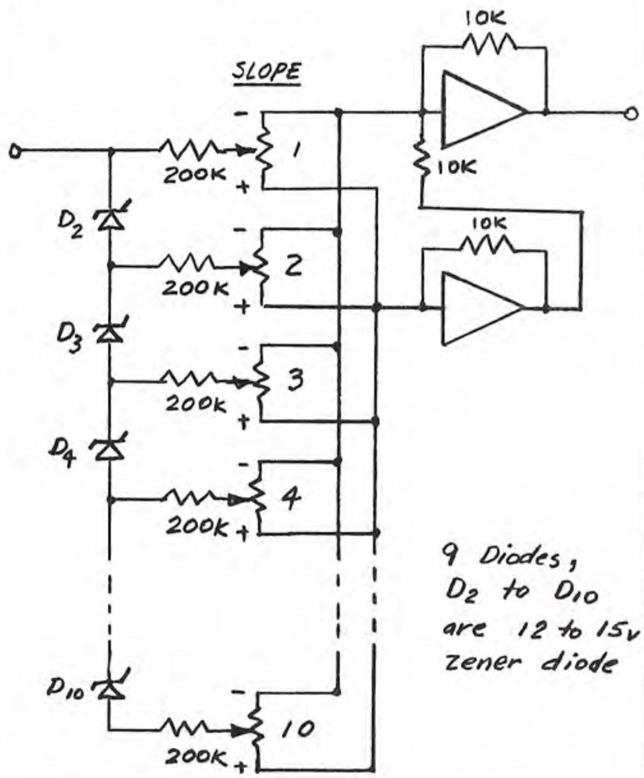
faster response

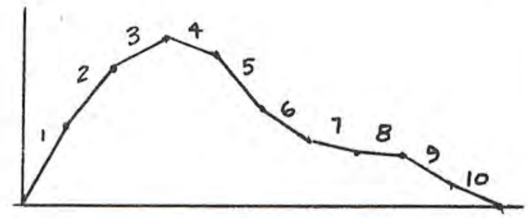
The mask can be under cut to improve response time.

The polaroid filter may be cut by using a hot resistance wire; the temperature can be adjusted by controlling current.

SEGMENTS FUNCTION GENERATOR

Segments function generator





Straight line approximated function can be generated with the aid of zener diodes and potentiometer.

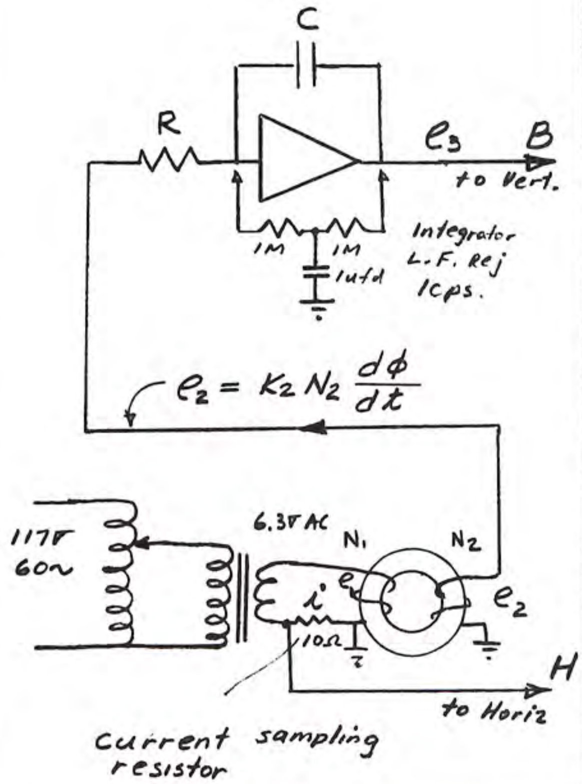
Zener diodes are normally cut-off. As sawtooth is applied zener diodes start conducting with some voltage intervals, thus making a line brake points.

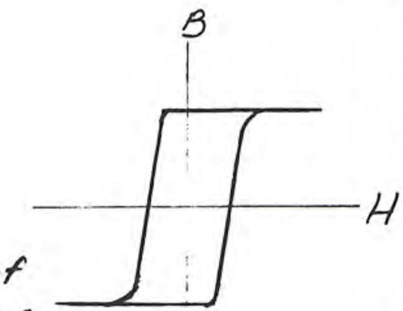
Slope of each segment is adjusted by the potentiometers.

Note that no external voltages are required.

B - H LOOP PLOTTING

B-H Curve Plotting





The voltage of the secondary, e_2, is given

$$e_2 = K_2 N_2 \frac{d\phi}{dt}$$

If we integrate e_2, the output of integrator e_0 will be proportional to flux ϕ,

$$e_0 = -\frac{1}{RC}\int K_2 N_2 \frac{d\phi}{dt}\,dt = \frac{-K_2 N_2}{RC}\phi$$

Since $B = \phi/A$

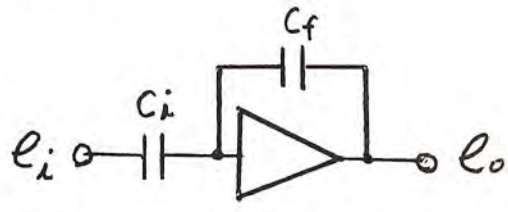
$$B = \frac{-RC}{K_2 N_2 A} e_0 \quad \longleftarrow$$

H is given

$$H = \frac{K_1 N_1}{\ell} i \quad \longleftarrow$$

CAPACITY MEASUREMENT (1 pf 10 ufd)

Basic idea



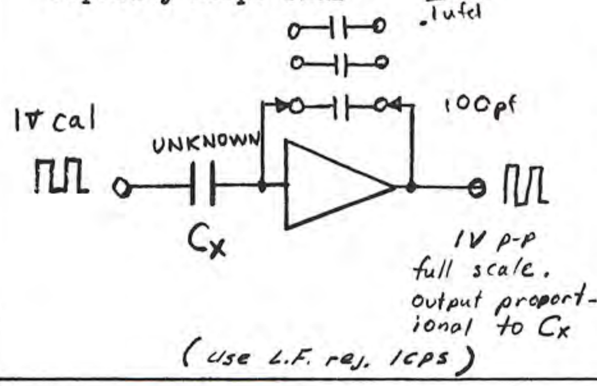
$$e_o = -\frac{C_i}{C_f} e_i$$

When capacitors are placed in input- and feedback, it will make an amplifier. Gain of this amplifier is $-C_i/C_f$, ratio of input C to the feedback C. Since the output voltage of the amplifier is proportional to the C_i, it is posible to measure capacitance.

Theoretically, this amplifier should have dc response but drift and leakage limits the low frequency response.

For figh frequency, charging current limits the response - smaller C be used.

Capacity 100pf~1uf



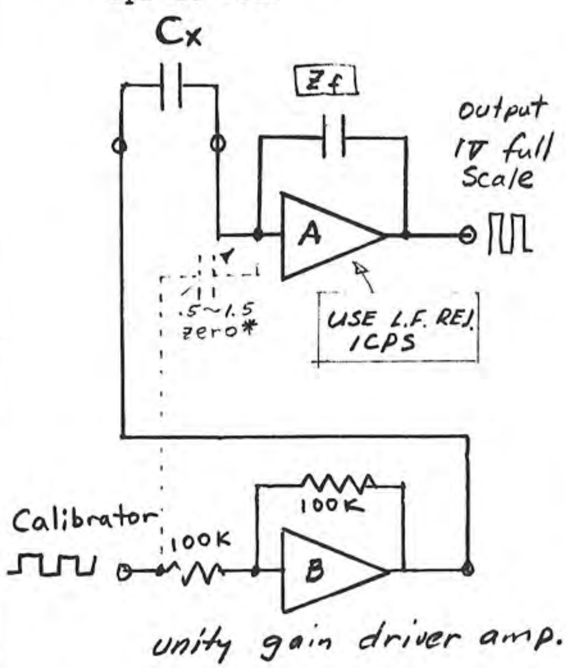
Unknown capacitor is compared to the precision internal feedback capacitor. When unknown C is same as feedback C the output voltage is 1 volt and it is directly proportional to C.

The output voltage canbe monitored by scope or meter.

The calibrator impedance is to high to drive higher capacitance therfore. use of isolation amplifier is recommended as shown below.

(use integrator L.F. rej. at 1cps.)

Widerange Capacity Meter
1pf to 10uf



Careful arrangement enable capacitance measurment for value 1pf to 10uf.

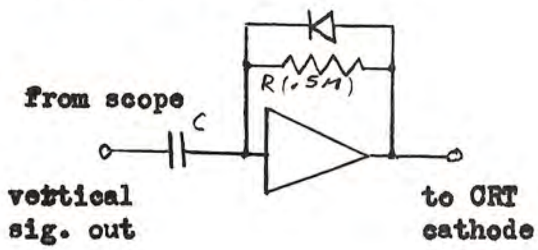
RANGE	Cal.	Z_f
0 - 10uf	10mv	.1
0 - 1uf	.1v	.1
0 - .1	.1v	.01
0 - .01	.1v	.001
0 - .001	1v	.001
0 - 100pf	10v	.001
0 - 10pf*	10v	.0001

* to compensate stray capacity, adjust neutralizing c for zero c.

5-22-61 Hm

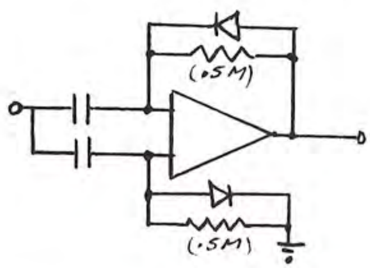
RISETIME BEAM INTENSIFIER

Risetime intensifier

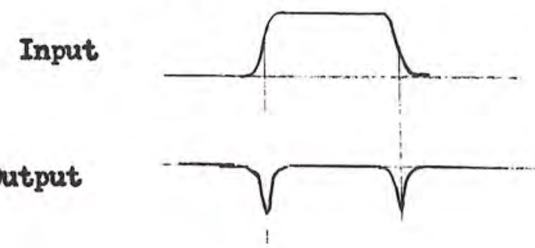


A differentiator can be used as a beam intensifier in certain experimental set up. Scope vertical signal out can provide signal to the differentiator and the output is fed to the CRT cathode. A word of caution, vert. signal output shuld not be monitored by the same scope. possible oscilation may result.

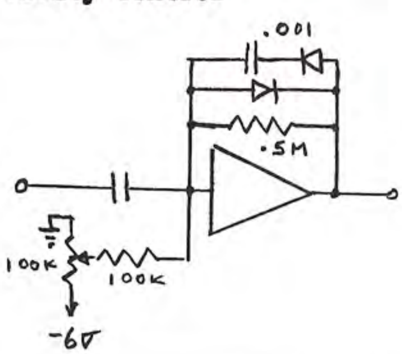
Rise & Fall time intensifier



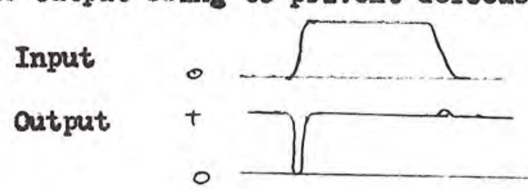
Appling signal to the both positive and negative grid, both rise and fall time can be intensified



Intensity control

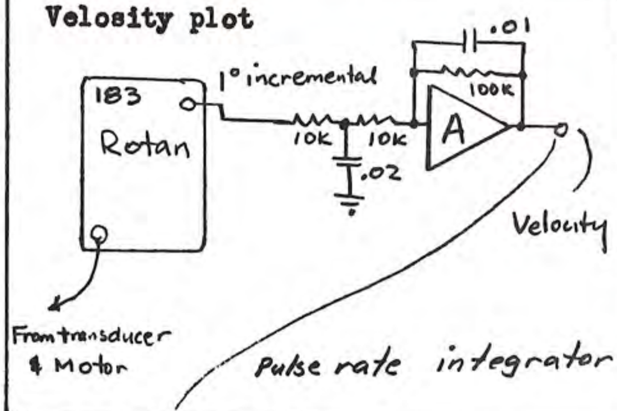


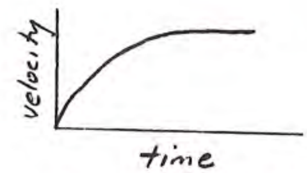
If the cathode is over drived a serious defocusing may result thus some means of maximum intensity limiter is disiered. In this circuit biassed diodes limit the output swing to privent defocusing.



VELOSITY ACCELERATION STUDIES

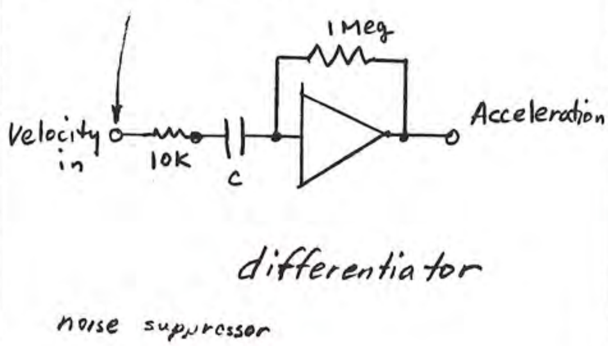
Velosity plot

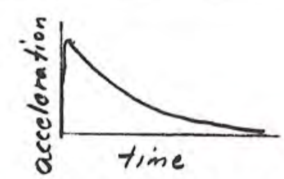




Rotational velocity may be obtained by integrating pulse rate, using the ROTAN 1° incremental pulse

Acceleration plot

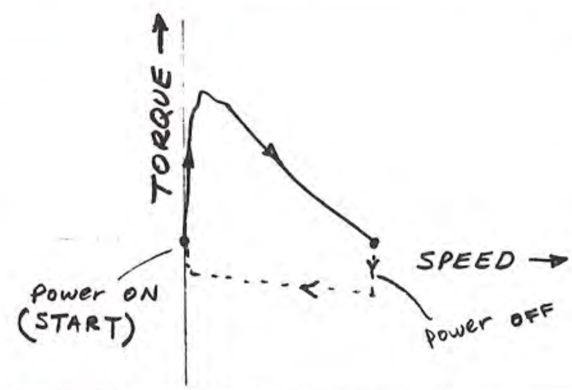




Velocity signal is differentiated to obtain acceleration. 10k resistor is added to suppress noise.

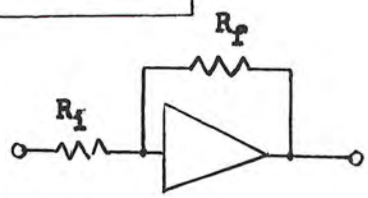
Speed - Torque Plot

X Y plot of velocity & acceleration gives a speed - torque plot. A typical motor characteristics may be obtained by starting and stopping the motor and observing the torque speed characteristics.



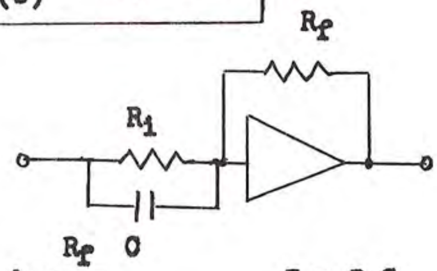
TRANSFER FUNCTIONS, e_o/e_i

$G_{(s)} = -k$



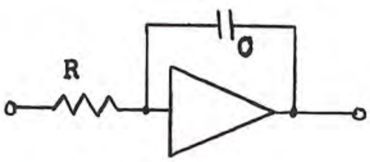
$k = \frac{R_f}{R_i}$

$G_{(s)} = K(Ts - 1)$



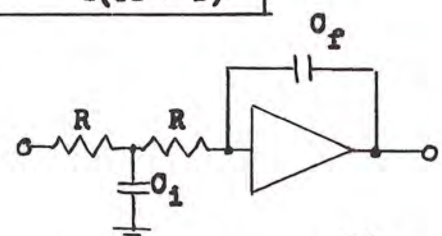
$k = \frac{R_f}{R_i}$ $\quad T = R_iC$

$G_{(s)} = -\frac{k}{s}$



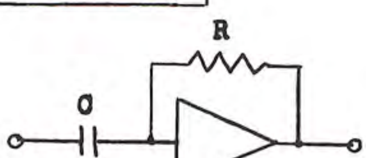
$k = \frac{1}{RC}$

$G_{(s)} = \frac{-k}{s(Ts - 1)}$



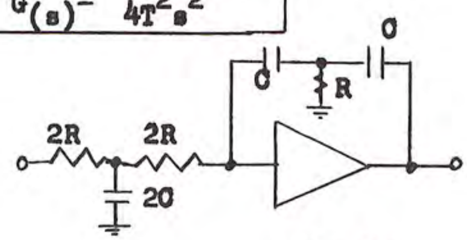
$k = 2RC_f$, $\quad T = \frac{RC_i}{2}$

$G_{(s)} = -ks$



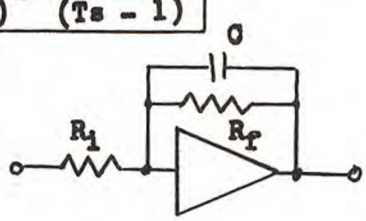
$k = RC$

$G_{(s)} = \frac{-1}{4T^2s^2}$



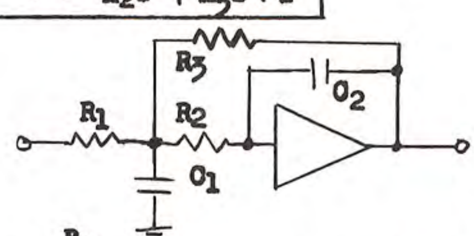
$T = RC$

$G_{(s)} = \frac{-k}{(Ts - 1)}$



$k = \frac{R_f}{R_i}$, $\quad T = R_fC$

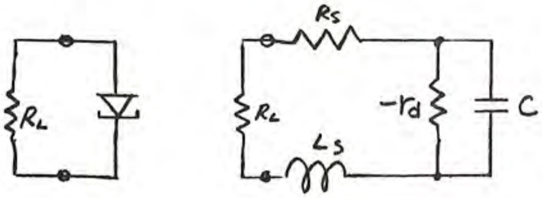
$G_{(s)} = \frac{-k_1}{k_2s^2 + k_3s + 1}$



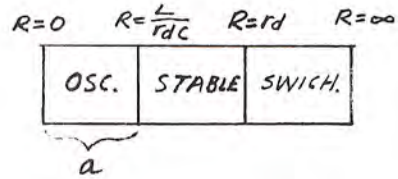
$k_1 = \frac{R_3}{R_1}$, $k_2 = R_2R_3C_1C_2$, $k_3 = (\frac{R_2R_3}{R_1} + R_3 + R_2)C_2$

TUNNEL DIODE STUDIES

Tunnel Diode Stability

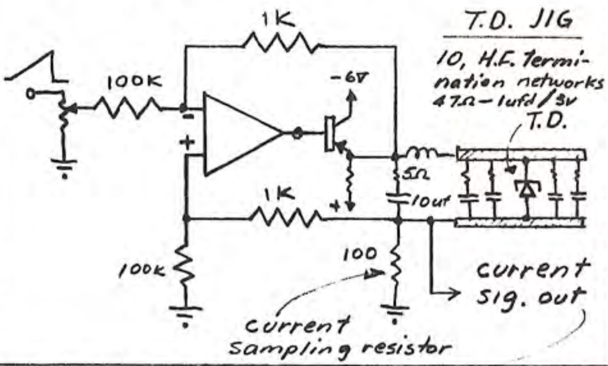


Tunnel diode stability criteria is given *



a. (can be made conditionally stable at low frequency)

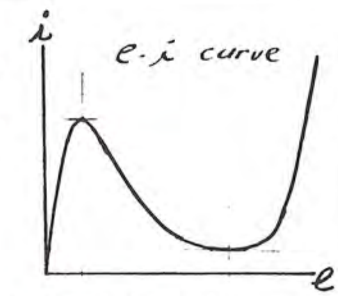
Tunnel Diode E-I curve



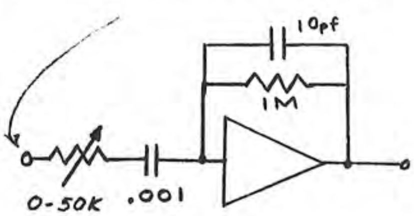
Operational amplifier with additional E.F. can drive tunnel diode with very low impedance.

T.D. jig stabilizes diode at High frequency.

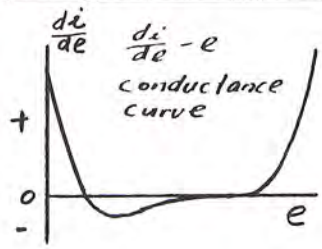
Thus tunnel diode may be driven by very slow ramp.



Tunnel Diode di/de curve



Linear drive of tunnel diode allow differentiation of current to obtain di/de curve



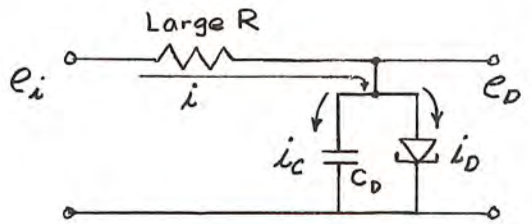
Tunnel diode quantum phenomenon may be observed at very low temperature.

Some tunnel diodes in liquid Helium indicate wiggles on the conductance curve.

* detail discussion of stability refer to "Some notes and applications on tunnel diodes" by Jack Rogers, Tektronix, Inc. , February, 1961

TUNNEL DIODE STUDIES, Risetime characteristics

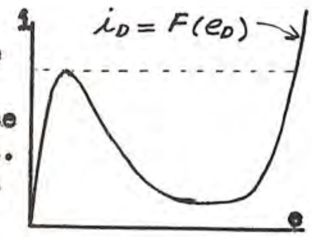
Tunnel Diode Switching



C_D = Equivalant diode capacity

Assumptions:

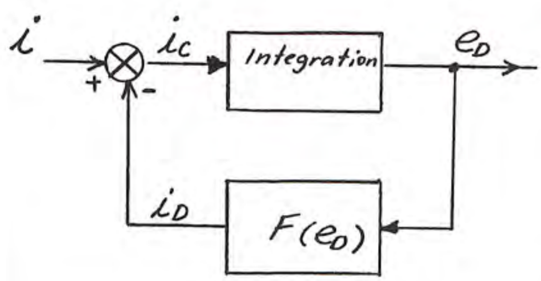
1) Leads inductance neglegible.
2) Diode capacitance assumed constant.
3) Constant current applied to the diode.



i = applied current, i_D = diode current

i_c = current to charge diode capacity

Block Diagram



Summing all the current at the node of e_D, we have

$$i - i_c - i_D = 0 \quad \ldots\ldots 1$$

$$i_c = i - i_D \quad \ldots\ldots 1a$$

$$i = \frac{ei - e_D}{R} \quad \ldots\ldots 2$$

$$i_c = C_D \int \frac{de_D}{dt} \quad \ldots\ldots 3$$

$$i_D = F(e_D) \quad \ldots\ldots 4$$

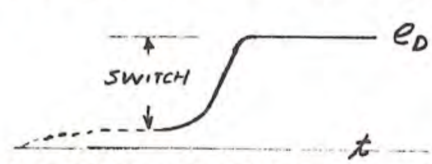
Integrating (3)

$$e_D = \frac{1}{C}\int i_c \, dt \quad \ldots\ldots 5$$

Substituting eq. (1a)

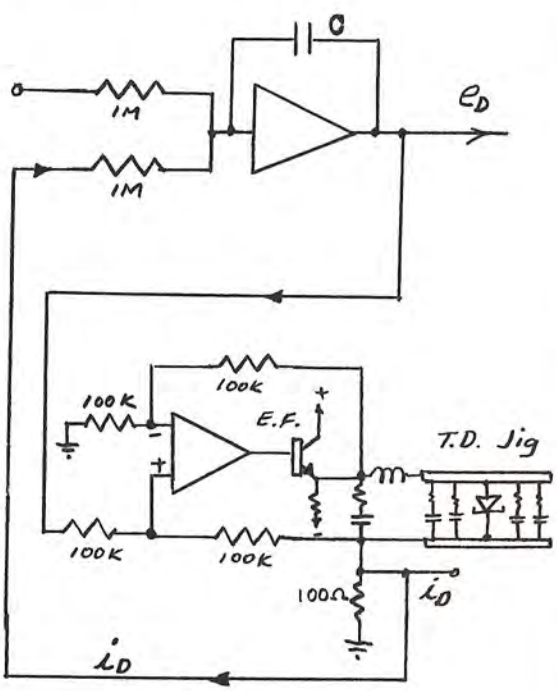
$$e_D = \frac{1}{C}\int (i - i_D)\, dt \quad \ldots 5a$$

The equation (4) and (5a) are represented by the block diagram, and operational amplifier circuit is shown at left.



If the integrating capacitor C is chosen 0.01 ufd for diode capacitance, C_D, 1 pf; the scaling factor will be 1 nsec real time equal to 10 msec analog time.

Analog Solution of Risetime*



* It is possible to compute diode capacitance from diode switching time.