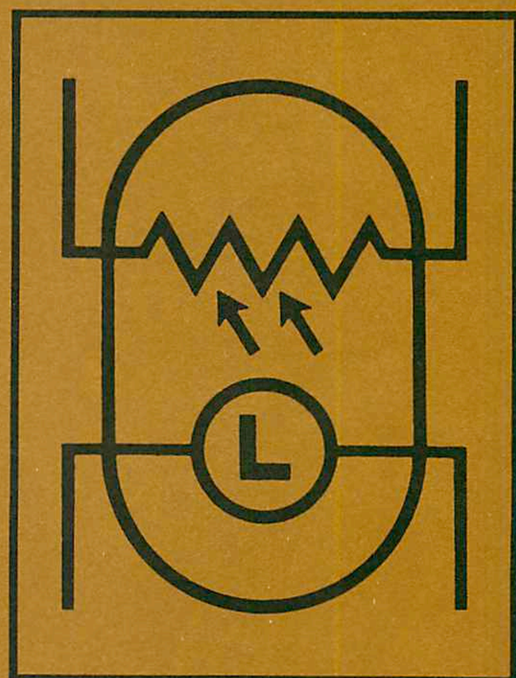
RAYTHEON **Raysistor**®

optoelectronic devices

CIRCUIT APPLICATIONS



GENERAL INFORMATION ON RAYSISTORS

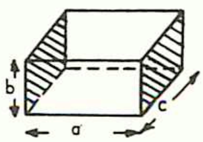
Raysistor is a Raytheon trade name for an opto-electronic component designed for applications in a variety of control functions, providing comparatively noise-free control of a-c or d-c signals over a wide dynamic range, without transients or contact chatter, and with a high insulation and electrical isolation between the signal and control circuit. Since there are no moving parts, Raysistors are exceptionally rugged and have inherently long life.

The Raysistor is basically a simple device. It consists of a light source and a photo-resistive element assembled in a light tight case. Different combinations of light sources and photocells give a wide range of operating characteristics. The photocells are poly-crystalline semiconductors of materials such as cadmium sulphide, cadmium selenide or lead telluride, and are selected for speed of operation, resistivity, power capabilities, etc. The light sources may be either incandescent filament or ionized gas. Since the ionized gas type of light source does not have the high thermal inertia of the filamentary light source, its response time to a change of the input control power is much shorter. The filamentary types on the other hand can be operated with much lower control voltages. The type used will depend on the specific application.

BASIC DESCRIPTION OF OPERATION

In the absence of light, photo-resistive elements of the types mentioned above look like insulators with all the carriers bound to the atoms that go to make up the individual crystal lattices. When some form of radiation (e. g. light from a filament or an ionized gas) is incident onto the crystal surface, the photon energy is absorbed by the lattice and a number of carriers are released as the atoms in this lattice are ionized. The individual crystal then becomes a conductor instead of an insulator. In a poly-crystalline structure these conductors add to provide a low resistance conducting path between suitably situated electrodes.

For a single crystal it can be shown that:



$$R = \frac{K}{Q}$$

Where R is the Resistivity/unit area of the crystal between the shaded surfaces, K is a proportionality factor dependent of the distance a, the mobility and life time of the carriers in the lattice, and Q is the number of incident photons.

In the Raysistor, then, any variation of the input to the light bulb (control) alters the illumination incident on the photocell (signal) and changes its resistance. Thus, for example, in a simple voltage divider circuit, the voltage across a fixed resistor in series with a photocell can be varied by altering the input to the light source. This feature of isolation between signal and control circuits is one of the primary advantages of the Raysistor, permitting the use of the device in a multitude of applications as photo choppers, variable resistors, solid state switches, relays, and voltage or signal isolators.

FACTORS AFFECTING RAYSISTOR PARAMETERS

TEMPERATURE

Ambient temperature does affect the value of "off" resistance, due to the increase in thermal energy of the carriers in the crystal structure. This change has a negative temperature coefficient.

An increase in temperature will also result in an increase in "switch off" speed but temperature does not affect the "switch on" time. (If it be desired to obtain a greater percentage change in resistance in the short interval following turn on, higher levels of illumination can be used.)

VOLTAGE

Under conditions of constant illumination, the photocell behaves as a pure resistance shunted by a very small fixed capacitance over a wide voltage range. With no illumination (control voltage zero) the resistance of the photocell is linear with respect to the voltage across it over only a narrow voltage range. Highest values of "off" resistance are obtained with small signal voltages.

LOAD

The load in the signal circuit must be large enough to assure that the photocell is not overdissipated under any condition. If the Raysistor is being used as switch, then the "on" and "off" times will depend on this value of R_L. The "on" time will decrease with smaller load resistance values and the "off" time will increase.

NOISE

In the range of 10 cps to 2 kcs with no voltage applied across the photocell terminals, the noise produced by the cell is equivalent to the thermal noise produced by a resistance (carbon or wirewound) of the same value as the photocell resistance.

When a voltage is applied across the photocell the amplitude of noise generated by the cells depends on two parameters:

1. The voltage amplitude across the photocell.
2. The level of incident illumination on the cell.

The noise amplitude is least with small signals and with maximum illumination levels. Typical values of noise are 2.0 μv rms over bandwidth 2 cps to 180 kcs with up to 50 mv d-c across the photocell and nominal control voltage. With 1.0 v across the photocell and nominal control voltage the noise output increases by approximately five times. This is greater than that produced by a carbon resistor of the same value as the photocell.

VOLTAIC EFFECTS

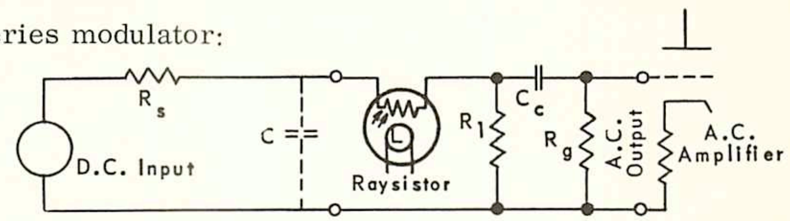
No measurable voltaic effects have been found with these types of photocells.

APPLICATIONS

PHOTOCHOPPERS

Choppers or modulators using photoconducting cells and modulated light sources offer the equipment designer several unique advantages. When used in a null amplifier, since the cell is well isolated, it is shielded from induced EMF's at the chopping frequency. This coupled with the purely ohmic behavior of the cell tends to eliminate the more common causes of null offset. Contact malfunctions which are the most vexing of all mechanical chopper problems simply do not exist. Since no voltage is present at the cell except that due to the d-c source being measured, there is no critical balance to be upset by environmental conditions as in the case of solid state devices using barrier junctions. Photochoppers can be used with sinusoidal modulation waveforms if required whereas mechanical choppers use essentially square waveforms and transistor choppers should be operated as switches for the most dependable performance. In the circuit description of photochopper circuits using Raysistors the two components of the Raysistor i.e. the photocell or signal end and the lamp or driving source shall be considered separately. The finite "on" and "off" resistances of the photoconducting cell modify the performance of the chopper and require greater emphasis to be placed on lead shielding. Two typical chopper circuit configurations are discussed below:

a. As a series modulator:



Defining modulation or conversion efficiency $\eta_1 = \dfrac{\text{a-c Output Peak to Peak}}{\text{d-c Input Signal}}$

Suppose R_s is small and R_g is large compared to R1 then $\eta_1 = \dfrac{\text{Epp (Output)}}{\text{Edc}}$

$$= \frac{R1}{R1 + Rmin} - \frac{R1}{R1 + Rmax}$$

Where Rmax and Rmin is the photocell resistance with minimum and maximum illumination respectively.

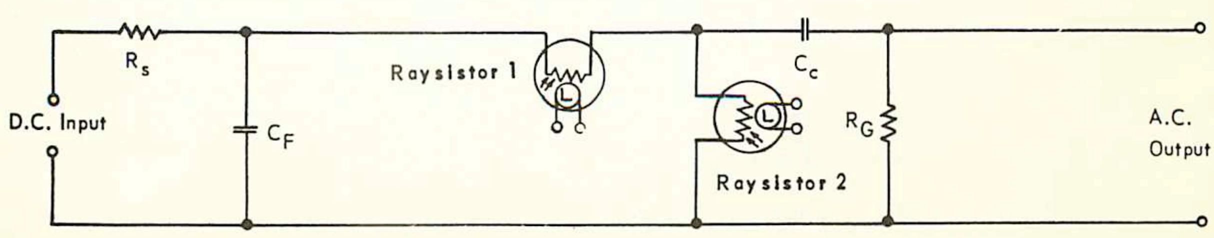
Now if R1 is chosen so that $\eta 1$ is a maximum then

when $R1 = \sqrt{Rmax \times Rmin}$

and $\eta 1 = \dfrac{\sqrt{Rmax} - \sqrt{Rmin}}{\sqrt{Rmax} + \sqrt{Rmin}}$

At low chopping frequencies from 30 cps to 60 cps the output waveform of the photochopper is nearly squarewave so that we get results comparable to other types of choppers. At higher frequencies the output waveform of the photochopper is more nearly sinusoidal and it becomes necessary to consider amplifier and detector characteristics before comparing relative efficiencies. As the frequency of the drive to the lamp of the photochopper increases, the lamp, having a certain amount of inertia, reduces its light output and as a result the difference between Rmin and Rmax is less. But, even if $\dfrac{Rmax}{Rmin}$ is only 9 then $\eta 1$ is still 0.5.

b. As a series shunt modulator:

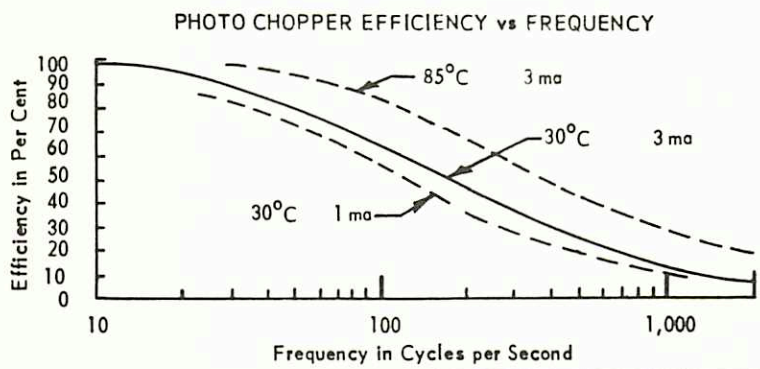


For this circuit efficiency $\eta 2 = \frac{Rmax - Rmin}{Rmax + Rmin}$

The ratio of $\eta 2$ to $\eta 1$ is given by:

$$\frac{\eta 2}{\eta 1} = \frac{\frac{Rmax - Rmin}{Rmax + Rmin}}{\frac{\sqrt{Rmax} - \sqrt{Rmin}}{\sqrt{Rmax} + \sqrt{Rmin}}} = \frac{Rmax + 2\sqrt{Rmax - Rmin} + Rmin}{Rmax + Rmin}$$

which shows that at high frequencies where $\sqrt{\frac{Rmax}{Rmin}}$ is nearly one, there is 6 db advantage in the series shunt circuit, but at low frequencies where this ratio is large, use of the simple series circuit may be more economical. However, the series shunt circuit provides a more symmetrical wave form and may result in less drift in null offset under varying environmental conditions.

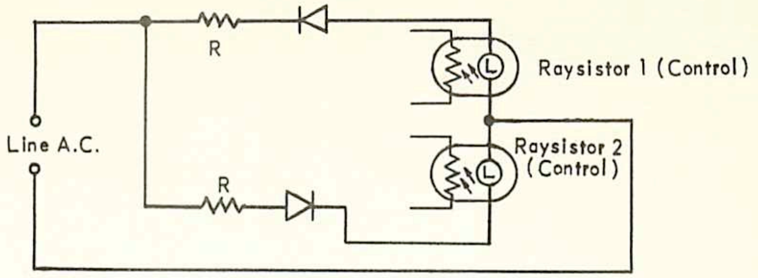


The improvement in efficiency of the series shunt circuit with temperature results from the shortened delay time for the conductivity of the photocell due to more rapid emptying of charge carriers caused by the increased thermal excitation.

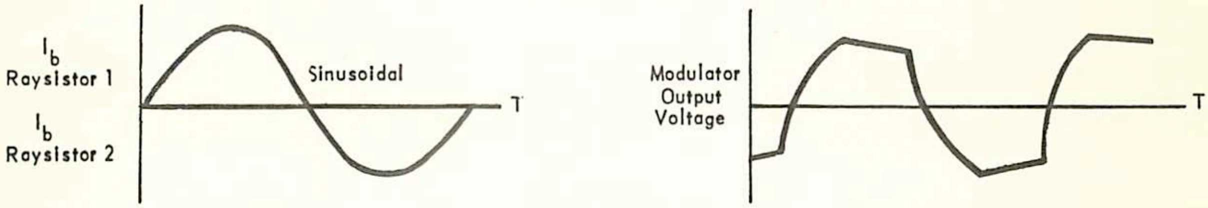
Drive Circuits for the Photochopper.

The neon lamp driving source must supply a sufficiently high peak voltage to ionize the gas; this may be obtained from the power line except in the rare instances where extreme isolation from a-c line pick up requires the use of another frequency. If the driving source has a sinusoidal a-c wave form, it is convenient to insert diode rectifiers and current limiting resistors in series with the lamps as shown in the following circuit. (next page)

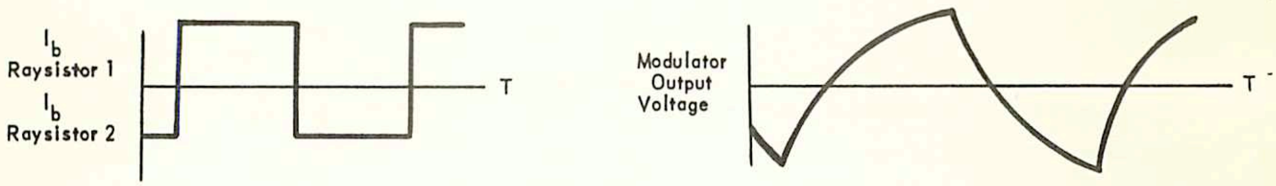
In some instances it may be advantageous to connect the diodes across the lamps in such a manner that the peak inverse applied to the diode cannot exceed the lamp's firing potential.



An illustration of the driving lamp current waveform and modulated output is shown below. Note that the output with square wave modulation of the lamp current is actually lower than with sine wave modulation. The reason for this lies in the decay characteristics of the photocell conductance. For example, if the light on the series cell is turned off well before the end of the cycle, the series resistance will rise to a value which is small compared to the load R_g yet large compared to the resistance of the shunt photocell in its "on" condition.



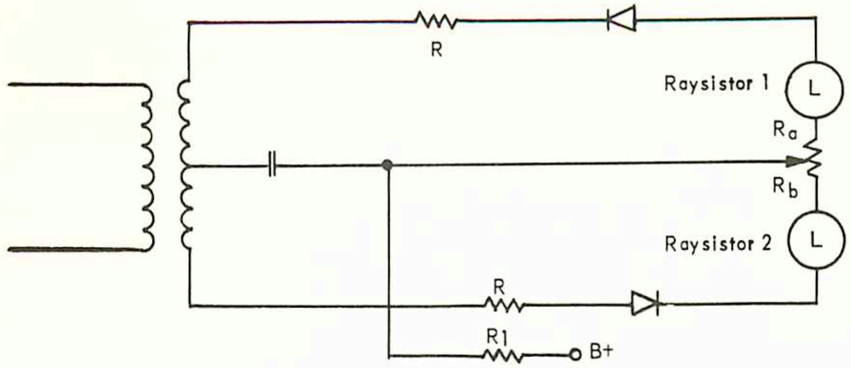
SINE WAVE DRIVING SOURCE



SQUARE WAVE DRIVING SOURCE

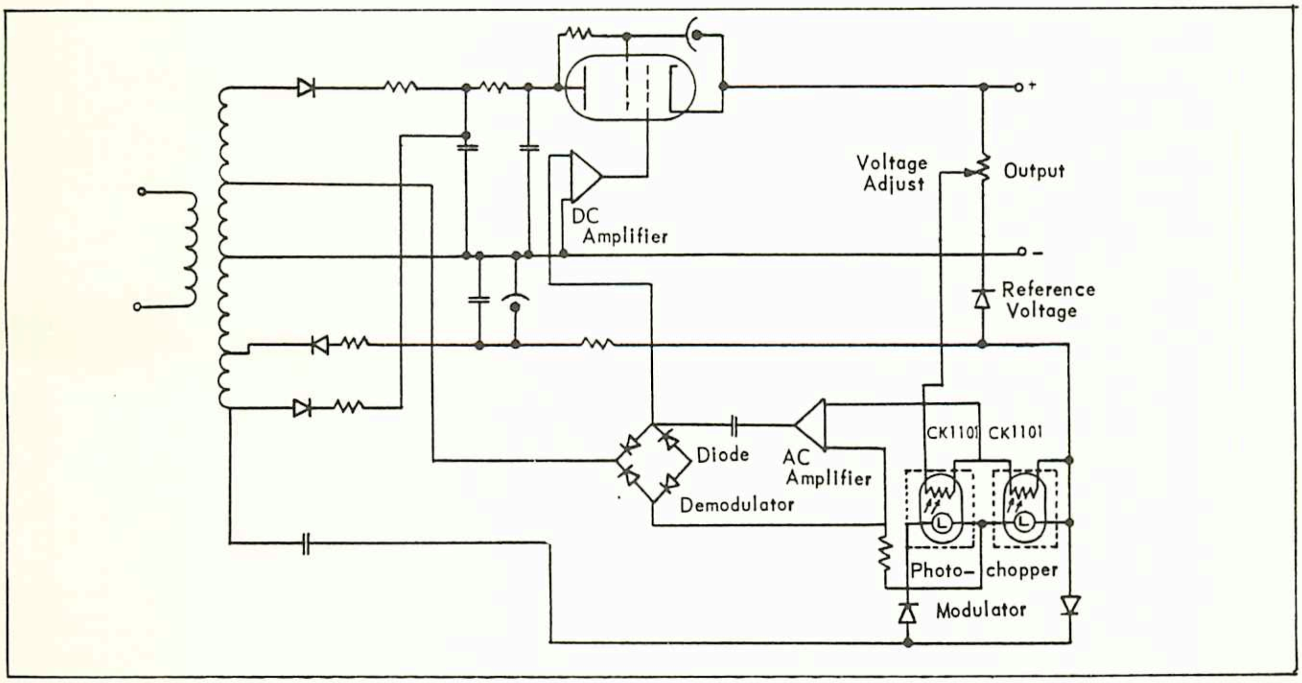
If it is desired to produce a true sine wave modulation with very low distortion then a circuit such as shown on the next page should be used. The constant d-c source (B+) insures that the lamps are continually on and that the a-c signal merely varies the lamp current about an average value. The slow decay of the photocell's conductance causes some phase shift between the drive and modulated output voltage, but the harmonic distortion is quite low.

1. Select Ra and Rb large enough to correct for lamp or transformer unbalance, but small compared to R or R1.
2. Select $R \sim \frac{E}{I}$ where I = I average per lamp, and $E = E_{Peak} - E_{VDL}$
   E_{VDL} = volts drop across lamp when ionized
3. Select $R1 \sim \frac{(B+) - E_{VDL}}{2I \text{ average}} - \frac{R}{2}$



For the ultimate in low drift or minimum null offset photochoppers can be used for both modulation and demodulation. In this case a very constant phase relationship is easily maintained and, by ganging electrically, synchronism is assured regardless of any variation in the drive frequency.

c. Photochopper stabilizer power supply to reduce long term d-c drift.



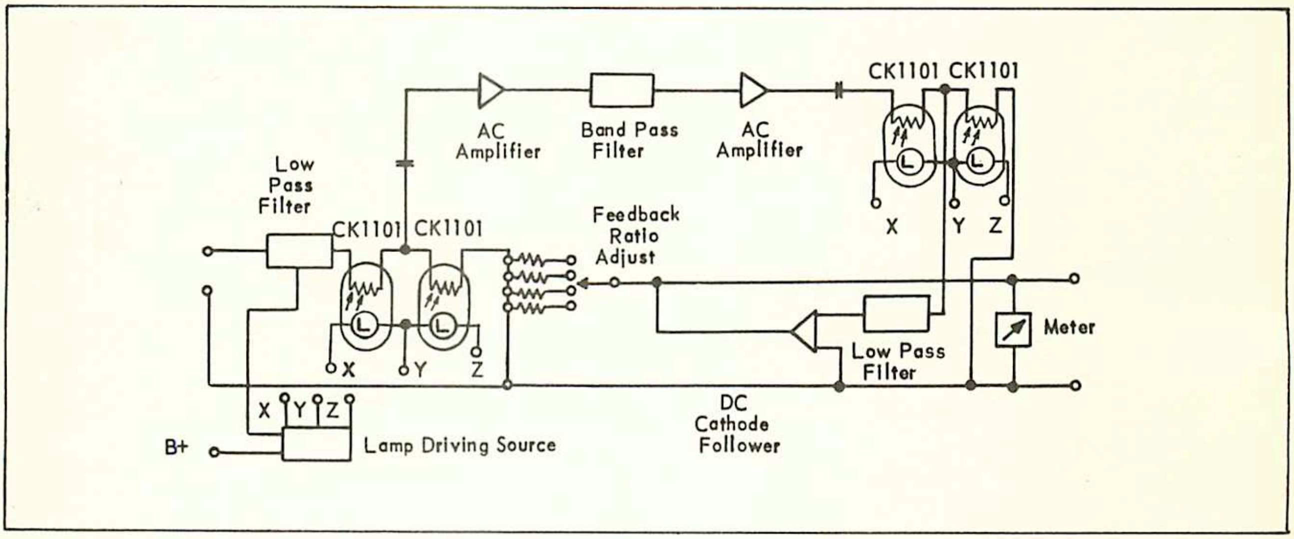
Advantages compared to other choppers:

1. Less noise than transistor choppers.
2. Avoids maintenance problem of mechanical choppers.
3. Free from intermittent contact troubles.
4. Insensitive to shock and vibration.
5. Inherent long life.
6. Free from contact bounce or jitter.
7. Low cost.

Notes on photochopper stabilized power supply.

1. If the null off-set requirements are not too severe, diodes are relatively cheap and suitable for high level demodulation as shown. If lower null off-sets are needed, then the chopping frequency should be at other than line frequencies and photochoppers used to demodulate as well as modulate.
2. The a-c amplifier bandwidth should be such that no appreciable phase shift occurs at the chopping frequency.
3. The phasing capacitor C is needed only when the demodulator is not a photochopper.

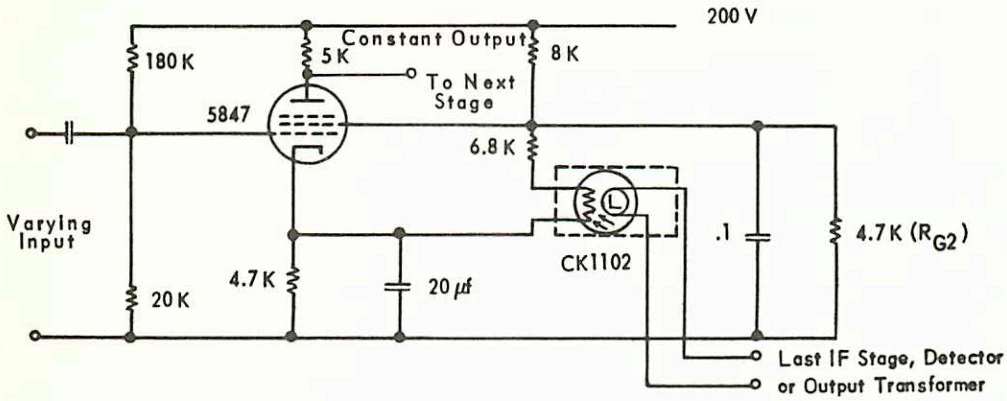
d. Photochopper stabilized d-c microvoltmeter.

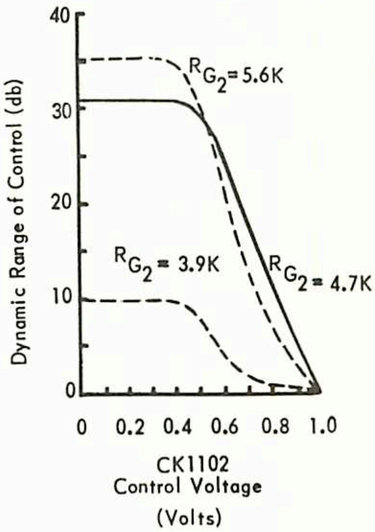


Advantages:

1. Photochoppers used in both modulator and demodulator circuits enable d-c levels to be as measured to a fraction of a microvolt.
2. Avoids maintenance problems of mechanical choppers.
3. Insensitive to shock and vibration.
4. Inherent long life and free from contact malfunction.
5. Free from contact bounce or jitter.
6. Easy to provide synchronous detection and demodulation using simple electrical coupling.

AGC VACUUM TUBE CIRCUITS





Advantages:

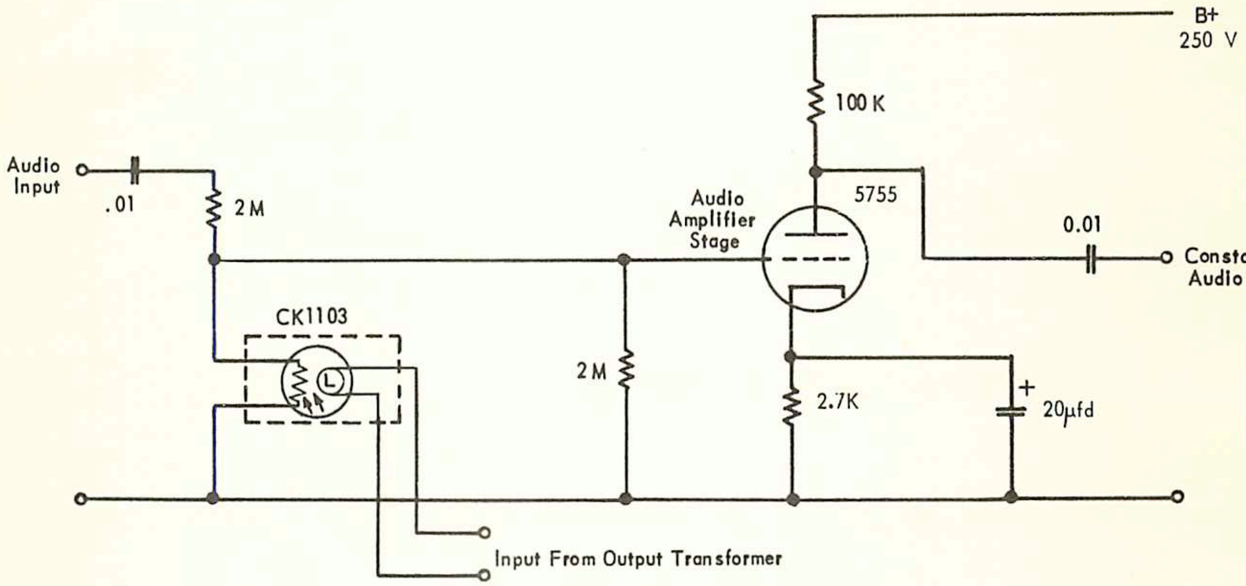
1. Wide Dynamic Range.
2. No change in bandwidth or frequency response.
3. No added noise.
4. Can be driven off undetected signals.
5. Good isolation.

Notes on vacuum tube circuit.

1. The dynamic range of control is about 20 db dependent on the overall gain of the stage.
2. The series 6.8K resistor ensures that the Raysistor photocell is not over-dissipated.
3. Change in R_{G2} will alter the shape of the control characteristics. In general, decrease in R_{G2} will decrease the range of control.
4. The circuit shown has a resistive plate load, but the application applies equally well to r-f and i-f amplifiers with only the plate and control grid circuits modified, and perhaps change in the decoupling condensers.
5. The use of the divider network at the G_1 circuit improves the long time stability of the stage.

CONTROL ELEMENT IN SSB SUPPRESSED CARRIER RECEIVERS

The Raysistor can be used to provide a simple remote or automatic volume control in any receiver but is particularly useful in SSB suppressed carrier receivers where otherwise fairly complicated circuits are needed. With SSB suppressed carrier transmission since there is no carrier when there is no modulation, the AVC system of a normal receiver operating off the r-f or i-f signal carrier will not function. The Raysistor can be used if part of the audio output of the receiver is fed back into the control light source, this varies the resistance of the photocell which can be used in place of the normal volume control. The Raysistor used in the circuit shown has a fast "on" action and a slow "off" action making it ideal for this type of application.



Advantages:

1. Fast "on" action (10 ms).
2. Slow "off" action (800 ms).
3. Lamp filament slow response provides an averaging affect.
4. Noise free control.
5. Remote or automatic control.
6. Good voltage isolation.
7. Wide dynamic range.

Very often working an amateur radio station using SSB transmission and reception entails the reception of a number of different stations of differing signal strengths at the antenna in rapid succession. Under these circumstances the a-f volume control has to be continuously adjusted. The Raysistor in the preceding circuit will provide an automatic control. The control circuit for the Raysistor can be driven directly off a-f.

Notes on circuit.

With no input to Raysistor control circuit

Resistance of photocell = 2 megohm

With full input to Raysistor control circuit

Resistance of photocell = 200 ohms

Hence the variation of the a-c signal output of the stage is from

$\frac{AEin}{3}$ down to $\frac{AEin}{10,000}$ (> 60 db range) where A is the stage gain.

Provided the a-f signal is small the photocell has very nearly an ohmic characteristic and very little distortion is introduced. This distortion will increase if the Raysistor is used at a later stage of the a-f amplifier chain.

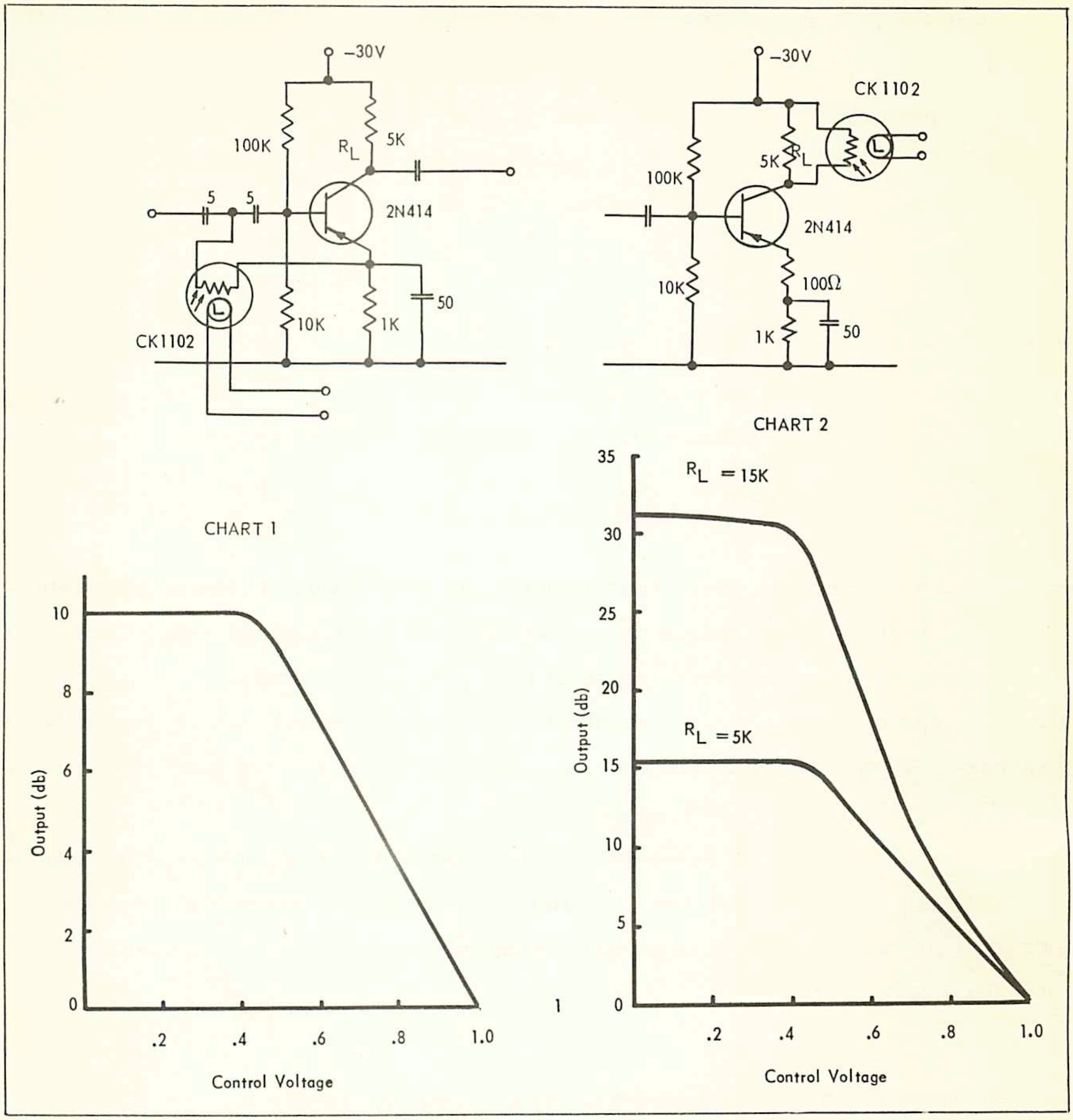
If a-f is used to drive the lamp (control circuit) of the Raysistor, then the thermal inertia of the filament will make any modulation of the photocell resistance inaudible except at very low frequencies.

The 2 megohm resistor in series with the photocell insures good h-f response of the circuit at all times and the 2 megohm shunting resistance insures that the operating conditions of the tube will not change with varying inputs to the Raysistor control circuit.

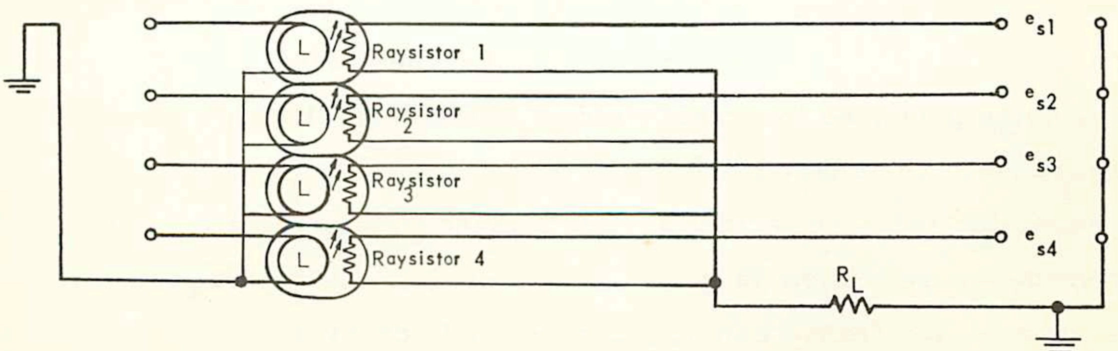
AGC TRANSISTOR CIRCUITS

The Raysistor can be used as shown for shunt control variation of the input current to the transistor. In this shunt circuit one end of the Raysistor is tied to the emitter so that the low frequency response does not deteriorate. Two coupling capacitors are used to isolate the photocell from the biasing circuits, this helps reduce the noise produced by direct current in the control. This circuit gives 10 db control range. See chart 1.

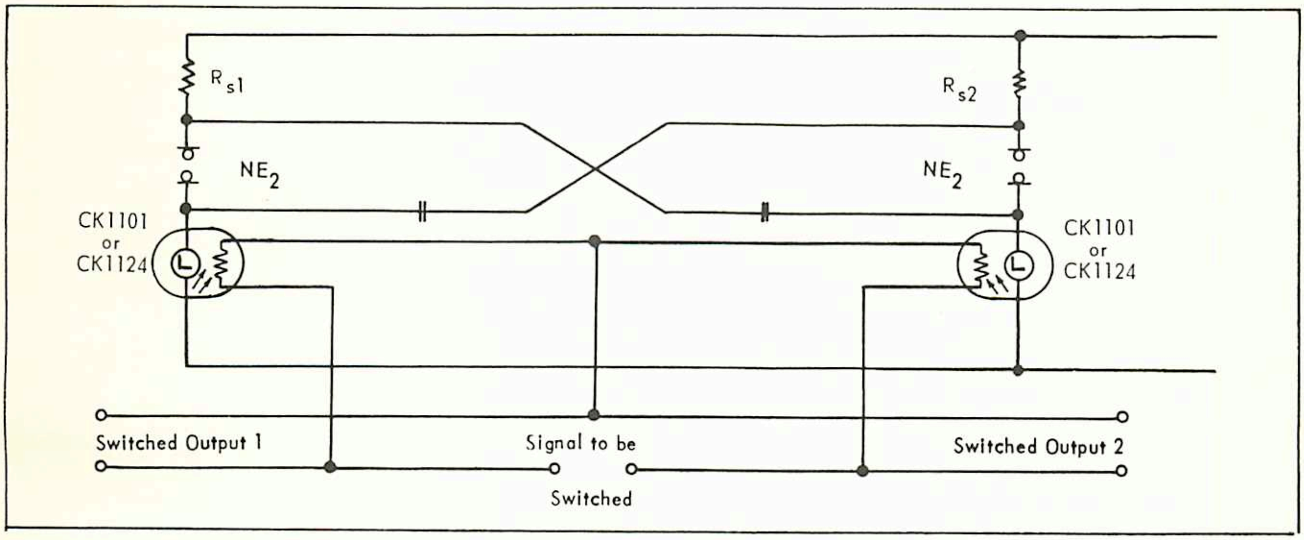
With the Raysistor in the collector circuit, with increasing input the collector load decreases, hence reduction in gain. In this circuit the control range is 15 db. By increasing RL this range can be extended. See chart 2.



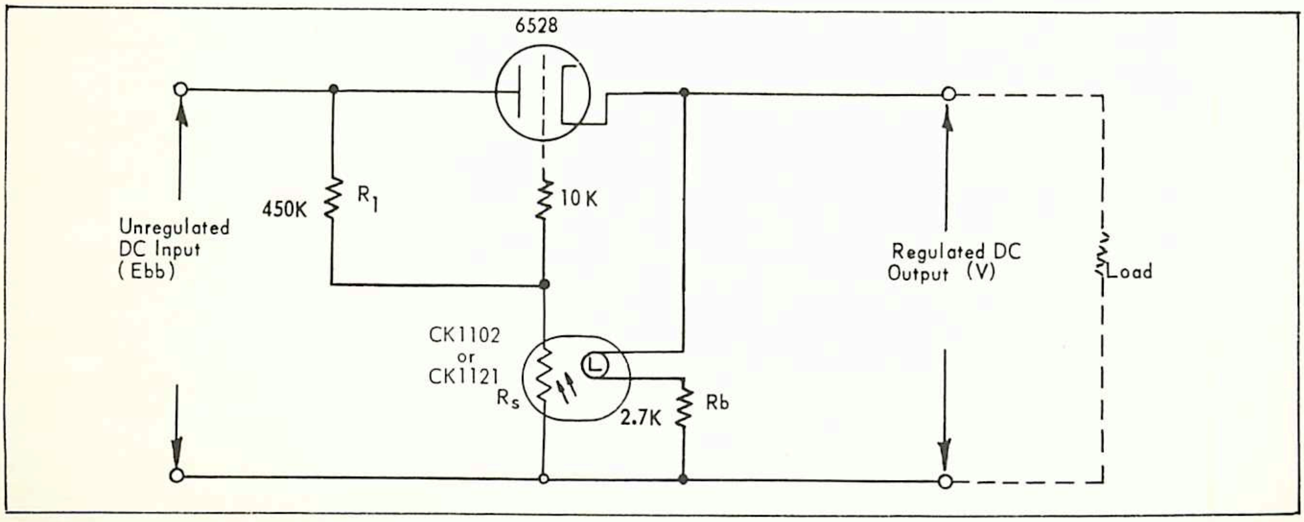
SWITCHING ELEMENT FOR LOW LEVEL SIGNALS



The Raysistor will provide low-noise switching free of transients or pedestals. Since the "off" time is normally slower than the "on" time, it is this "off" time that determines the maximum switching rate. Any number of the devices can be switched in succession provided a means of sequentially switching the control circuits is provided. The Burroughs BX3000 will switch 10 Raysistors in succession when suitably triggered. Where large signals are to be switched, a suitable series resistance must be added to avoid over dissipating the cells. A two Raysistor sequential switch using a multivibrator type of circuit is shown below.



LOW COST REGULATED POWER SUPPLY



The CK1102 in the above circuit provides a very simple type of regulated power supply.

Analysis of circuit parameters.

Suppose Ebb = 300 v

Since the grid to cathode voltage of the series tube will be approximately 0 volts compared to 300 v

$$\frac{R1}{Rs} = \frac{Ebb - V}{V}$$

Selecting R1 to limit the dissipation in Rs to 50 mW, and making it equal to Rs Rs for maximum power dissipation

$$\frac{Ebb^2}{4\,R1} = 50\text{ mW}$$

$$R1 = \frac{300^2}{4 \times 50 \times 10^{-3}}$$

$$= 450K$$

Rb is selected so that there is appreciable bulb current flowing and then the change in Rs will be as fast as possible using this type of device.

Let $X = \frac{dRs}{dVL}$ Where Rs is the Raysistor resistance and VL = Voltage across Raysistor Lamp.

Then $dVL = \frac{RL\,dV}{RL + Rb}$ Where RL = Lamp Resistance

$dVs = \frac{dRs\ R1\ Ebb}{(Rs + R1)^2}$ Where V_S = Voltage across Resistor

$$\text{and } dVg = \frac{X\,dVL\ R1\ Ebb}{(Rs + R1)^2} - dV$$

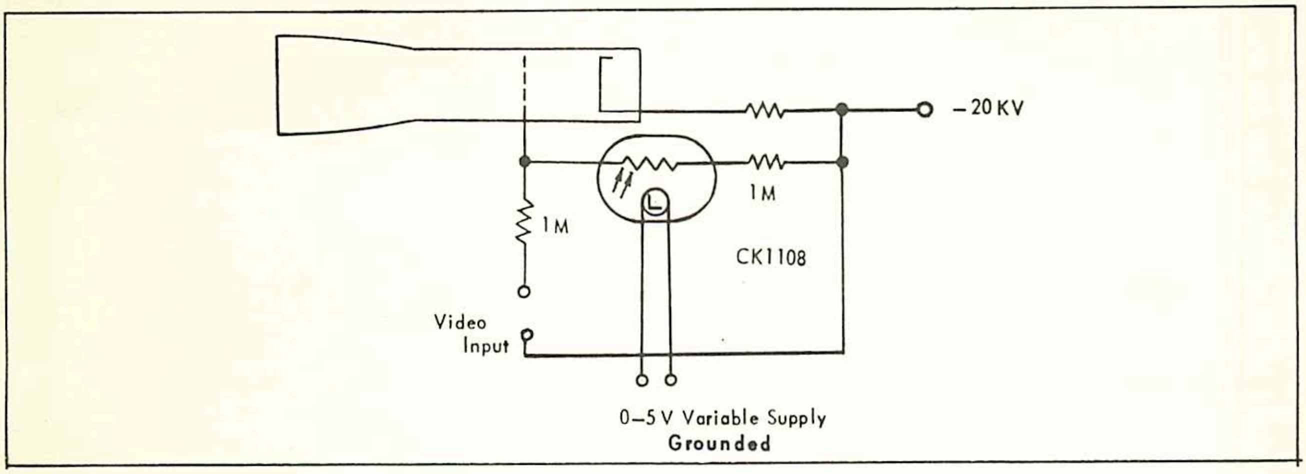
$$\text{and } diL = \left[\frac{X\ RL\ dV\ R1\ Ebb}{(RL \pm Rb)\,(Rs + RL)^2} - dV \right] Gm$$

$$Z\text{ out} = \frac{dV}{diL} = \frac{(RL + Rb)\,(Rs + R1)^2}{Gm\,[X\ R1\ RL\ Ebb - (RL + Rb)\,(Rs + R1)^2]}$$

As $X \longrightarrow 0$ so $Z \longrightarrow \frac{1}{Gm}$

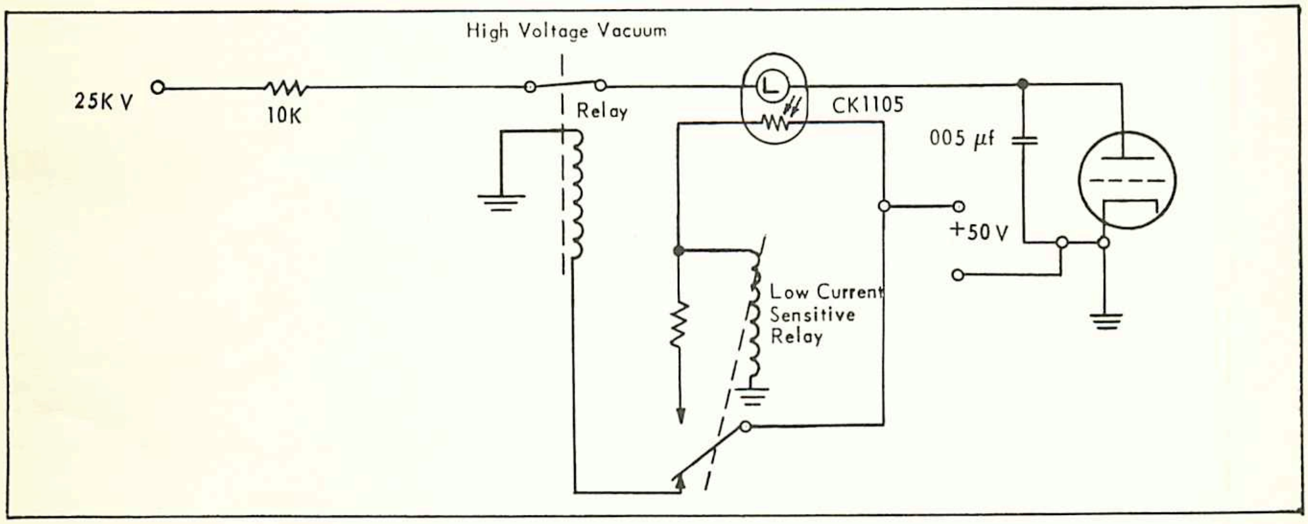
As used in this circuit the output impedance is approximately one ohm and good regulation is obtained with an output of 100 v for a variation of input over the range 200 volts to 400 volts.

REMOTE CONTROL AND HIGH VOLTAGE ISOLATION



The CK1108 will provide up to 25 Kv isolation and in this circuit will give a range of approximately 60 db. The lamp filament provides an automatic averaging effect because of its thermal inertia so a similar circuit could be used to provide an automatic contrast control if the video signal is amplified to drive the lamp circuit.

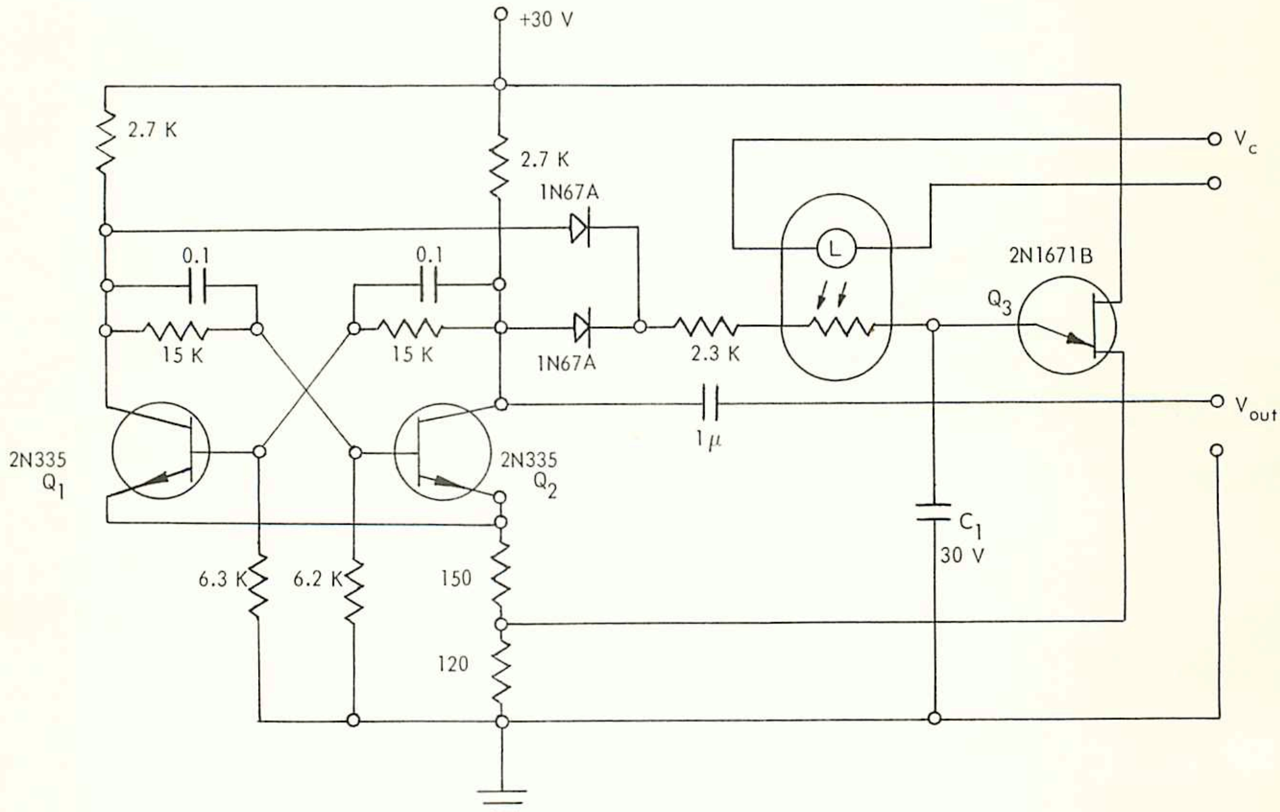
HIGH VOLTAGE OVERLOAD PROTECTION



Any arc or intermittent short circuit in the tube causes an increase in the average current through the Raysistor lamp and reduces the photocell resistance. The low current relay is activated which in turn pulls in the high voltage relay to open the circuit and prevent damage to the circuit components. The Raysistor shown in the circuit has a neon lamp, if higher current levels are required then the filamentary CK1108 can be used. As shown the response time of the Raysistor is quite rapid since there is a current through the lamp circuit continuously.

VOLTAGE CONTROLLED OSCILLATOR

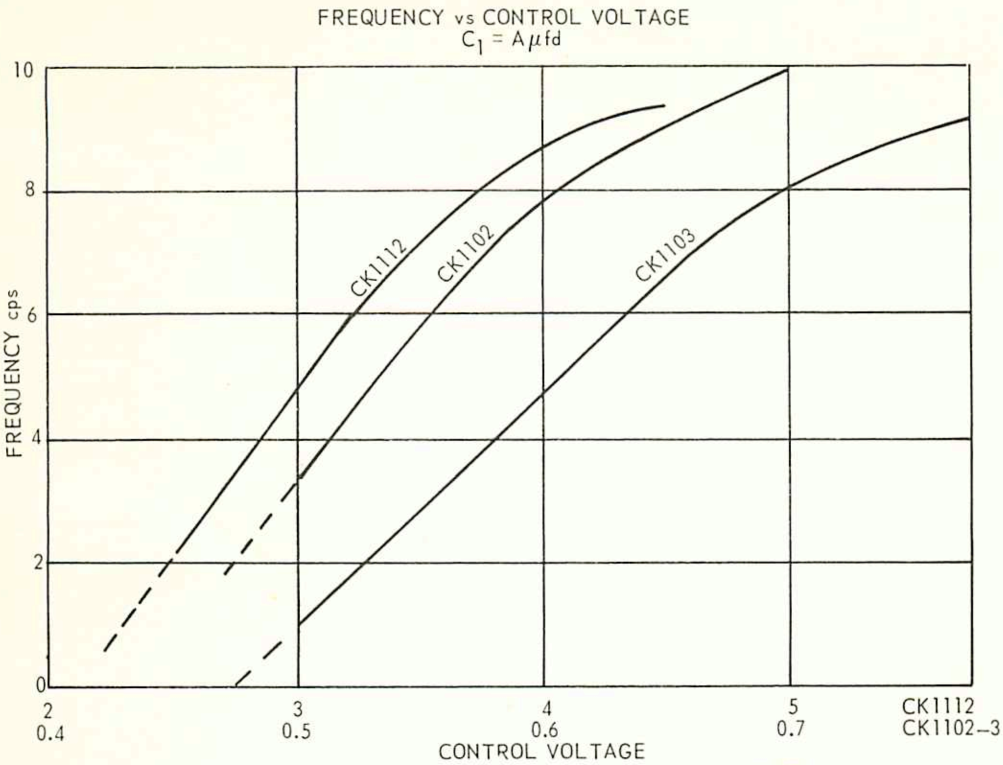
The Raysistor can be used in a voltage controlled oscillator whose frequency is proportional to the voltage Vc applied to the control terminals of the Raysistor. The multivibrator is driven at half speed, thus producing a square wave at the output terminals.

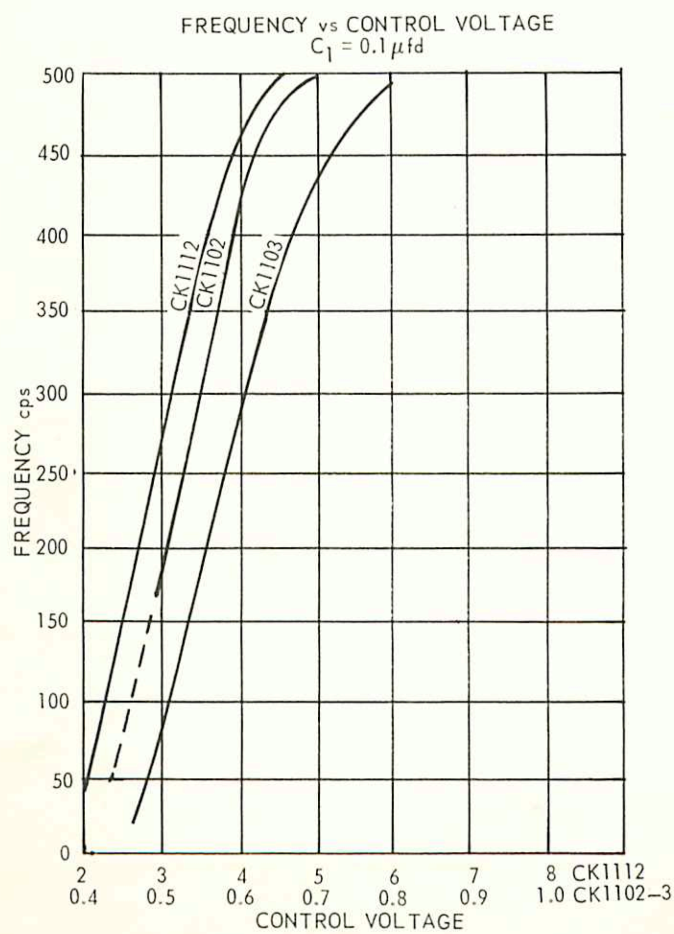


Transistors Q1 and Q2 form a bistable multivibrator which is driven by a unijunction transistor Q3. The frequency of oscillation of this unijunction transistor is determined by the Raysistor signal or photocell resistance in the emitter lead of Q3 and the capacitor C1. As Vc is increased, the Raysistor signal resistance decreases. The charging time constant for C, therefore is reduced and the frequency of oscillation increases. Typical curves of output frequency as a function of Raysistor control voltage are shown for selected Raysistor types and illustrative values of C.

Advantages:

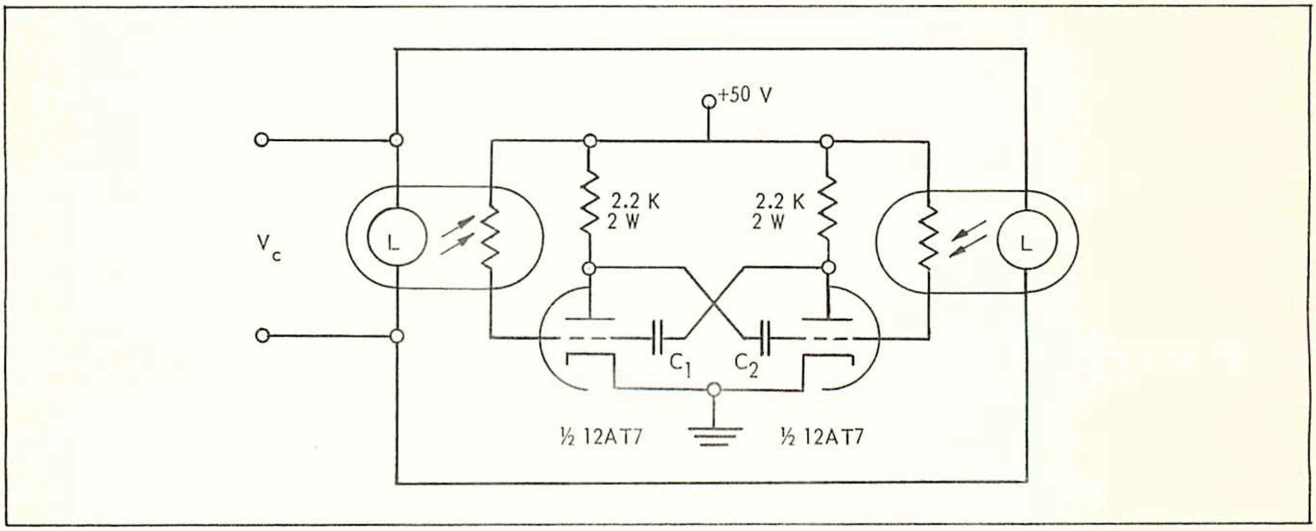
1. Oscillator is isolated from the control voltage, thus simplifying remote control.
2. Good linearity of frequency control.
3. Wide range.


FREQUENCY vs CONTROL VOLTAGE
C_1 = A μfd
FREQUENCY cps
10
8
6
4
2
0
CK1112
CK1102
CK1103
2
0.4
3
0.5
4
0.6
5
0.7
CK1112
CK1102–3
CONTROL VOLTAGE


FREQUENCY vs CONTROL VOLTAGE
C_1 = 0.1 μfd
FREQUENCY cps
500
450
400
350
300
250
200
150
100
50
0
CK1112
CK1102
CK1103
2
0.4
3
0.5
4
0.6
5
0.7
6
0.8
7
0.9
8 CK1112
1.0 CK1102–3
CONTROL VOLTAGE

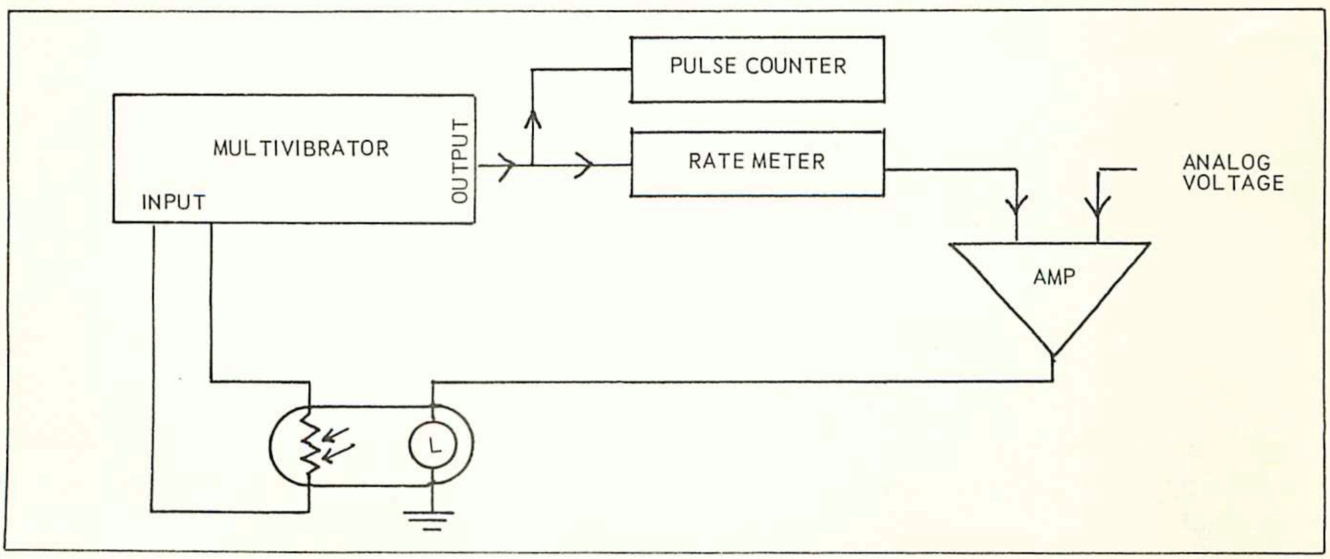
WIDE RANGE FREQUENCY GENERATORS & ANALOG-TO-DIGITAL CONVERTER

A wide range frequency generator can be remotely controlled by using the Raysistor as indicated. Raysistors are used in the grid circuit to obtain a symmetrical wave form, and the capacitors are chosen to produce the required frequency range.



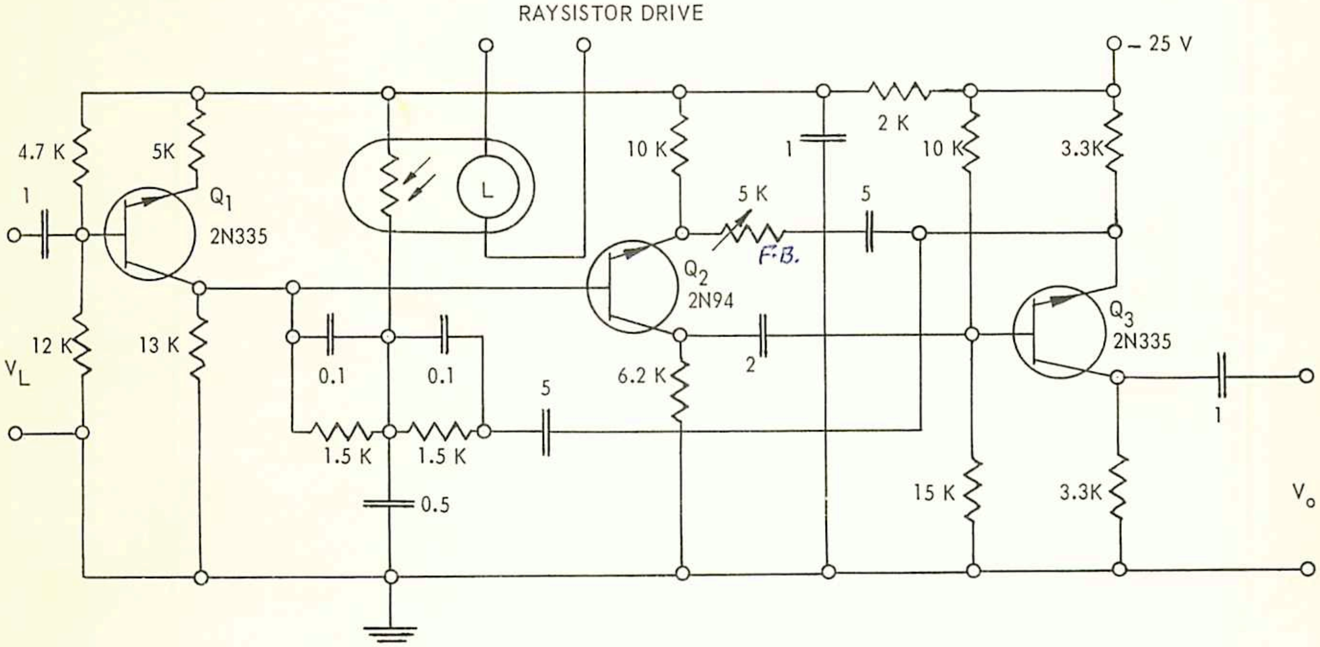
In the circuit shown, the output of the plate coupled multivibrator can be changed from below 5 cps to above 5, 000 cps by an input control voltage variation of 0.4 volt.

This circuit can also be used as an analog-to-digital converted by coupling the output to a rate meter to obtain an output proportional to the frequency. This signal is then fed in opposition to the analog voltage and the error signal is amplified and applied to the Raysistor control voltage terminals. This forces the oscillator to operate at a frequency proportional to the error signal voltage.



TRACKING FILTER

An amplifier using negative feedback applied through a notch filter to provide frequency selective feedback becomes a tracking filter. A Raysistor may be used to control the resonant frequency of the notch filter as shown.

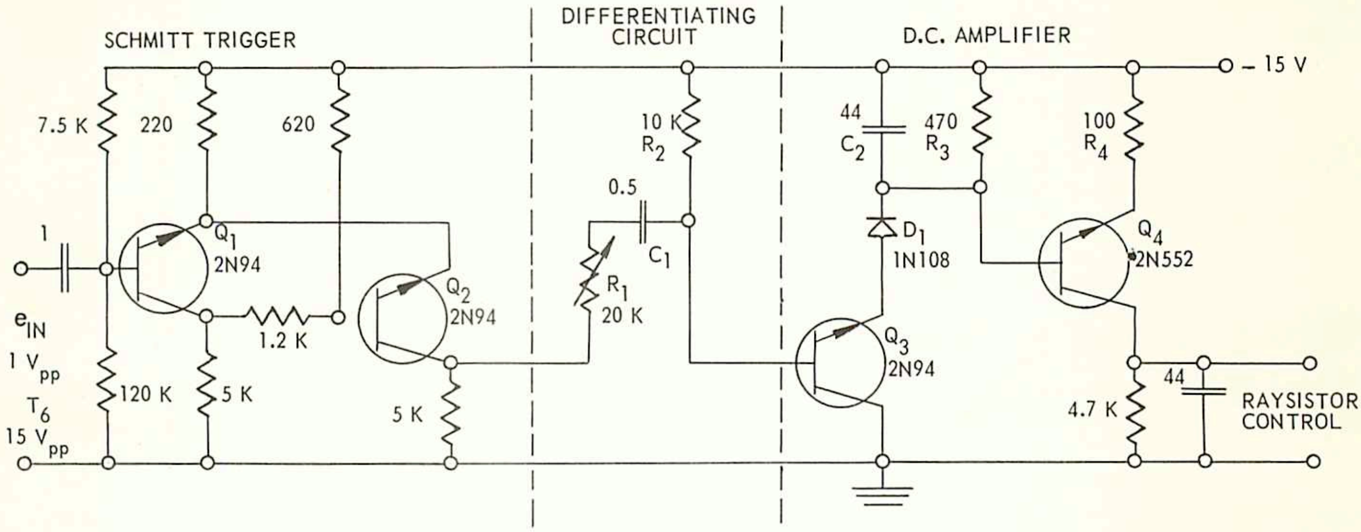


The feedback contains all the frequencies in the signal except those shunted by the notch filter, producing a tuned circuit effect at the output of the amplifier. Feedback level is adjusted by the 5, 000 ohm potentiometer, thus controlling also the Q of the output response curve.

For the component values shown, and with the control adjusted for a Q of 5, the filter tracks from 800 cps to 1, 200 cps.

By using a special drive circuit for the Raysistor the filter can be made to automatically follow an applied signal frequency. A Schmitt trigger, a differentiating circuit and a d-c amplifier can be used to provide a signal whose amplitude varies with the applied frequency.

For the circuit shown, the input to the Schmitt trigger is a sine wave signal (800 cycles to 1. 2 kc) which can vary from 1 volt to 15 volts (peak to peak), and the output is a 10-volt square wave, varying in amplitude ± 5 per cent. The square wave is then differentiated. Note that R1 is adjusted to give the required change in Raysistor control current due to the change in the area of the differentiated wave with frequency. The signal is then rectified to produce a d-c voltage proportional to the average value of the differentiated wave form. The d-c voltage is amplified and applied to the Raysistor control element. Current magnitude is adjusted by varying R4.

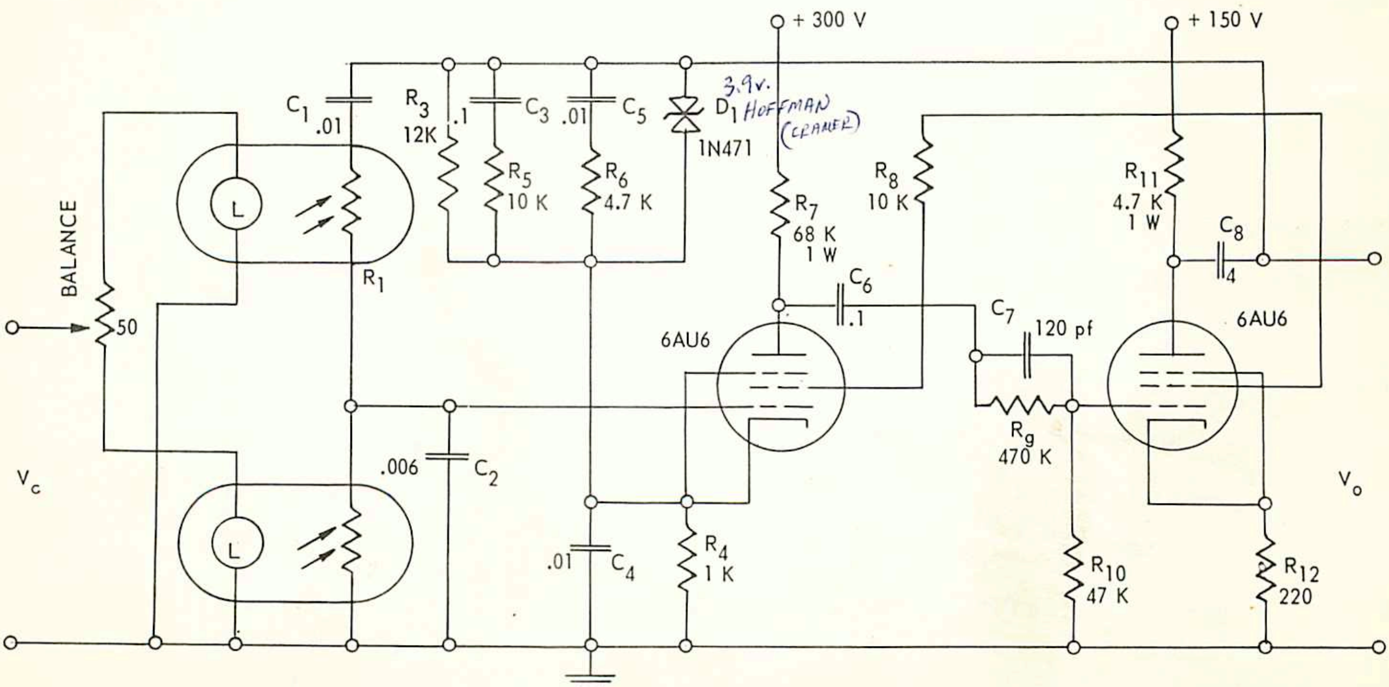


Depending on the type of Raysistor used and the variation in signal resistance required, an additional stage of d-c amplification (or a-c amplification ahead of the rectifier) may be necessary.

Advantages:

1. Center frequency of filter follows applied frequency.
2. Provide variable Q adjustment.
3. Provide high Q.

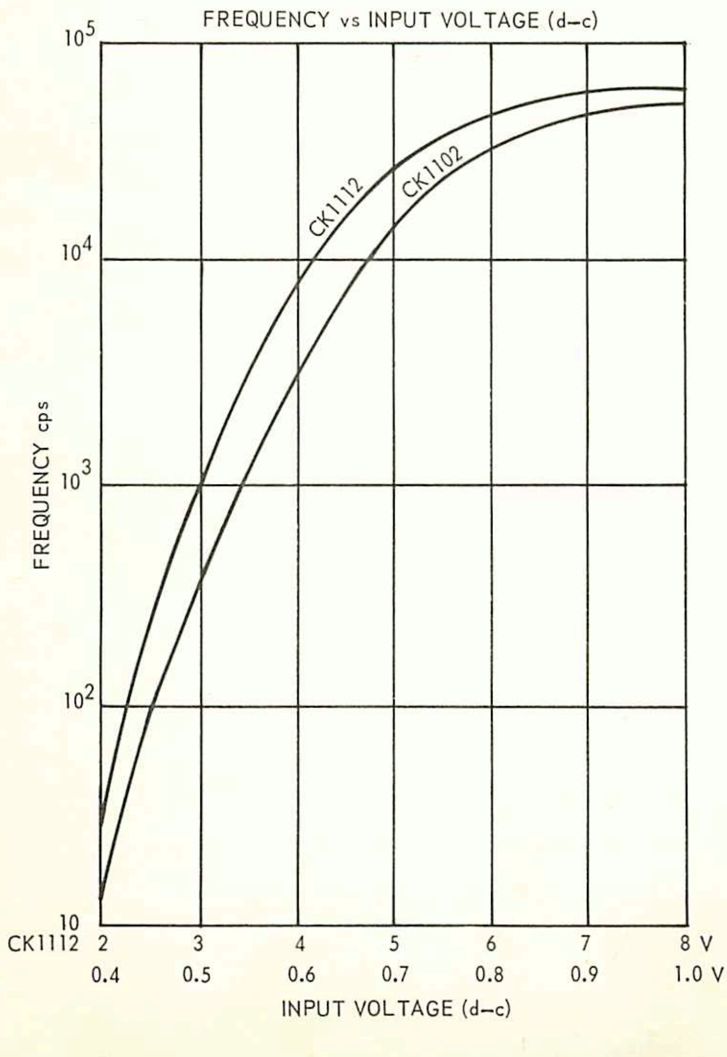
VOLTAGE-CONTROLLED WIEN BRIDGE OSCILLATOR



A Wien bridge oscillator is a two-stage amplifier wherein the output is fed back to the input through a two-path phase shift network. The oscillation occurs at that frequency for which there is a 360° phase shift around the complete loop.

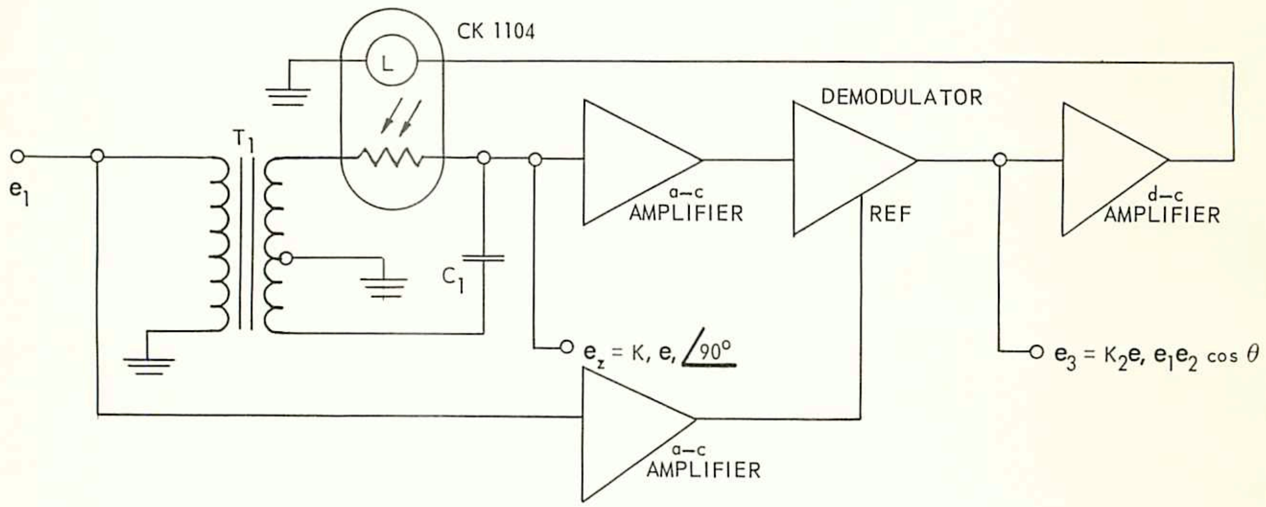
The feedback to the input grid through C1 and R1 is positive and produces the required regeneration that causes oscillation. The feedback to the cathode through R3 is negative, and this tends to limit the amplitude. Note that R3 is combined with a low voltage double anode zener diode which limits the amplitude both by loading V2 and by increasing negative feedback. C4 improves the high frequency performance and the R3, R5, C3, R6 and C5 network provides increasing feedback as the frequency rises. R9, C7 and R10 compensate roughly for the response characteristic of the phase shift network R1, R2, C1 and C2.

The output of this circuit is reasonably sinusoidal and has constant amplitude (± 1 db) over the frequency range of 10 cycles to 50 kc.



CONSTANT 90° PHASE SHIFTER FOR AUDIO RANGE

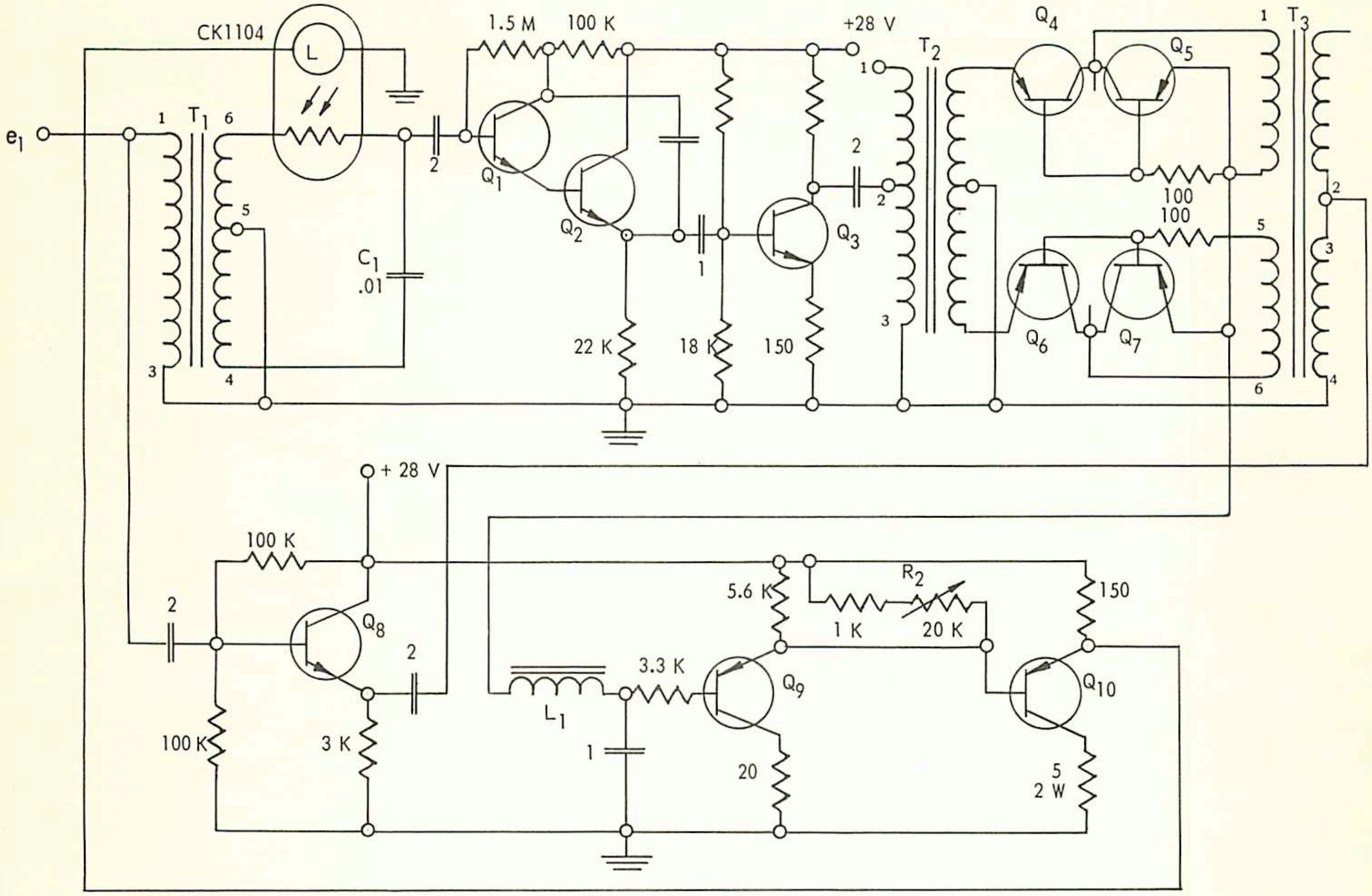
The Raysistor may be used as a variable resistance in a servo loop providing a constant 90° phase shifter for signals over an appreciable audio range.



Referring to the block diagram, the input signal e1 is phase shifted by 90° when the Raysistor signal resistance is equal to X_{c1}. This signal e2 = K1 e1 $\angle 90°$, is amplified and fed into a phase sensitive, synchronous demodulator whose reference, e1, is also amplified through a similar amplifier so that no additional phase shift occurs in the reference.

The demodulator output is K2 e1 e2 cos θ, where θ is the phase angle between e1 and e2. When θ = 90°, e3 is zero, but as the frequency of e1 is changed the impedance of C1 will vary and cos θ will become a finite value. The d-c amplifier will then send a control voltage to the Raysistor which will change the Raysistor signal resistance to equal the impedance of C1 and, in turn, causing the phase between e1 and e2 to equal 90°.

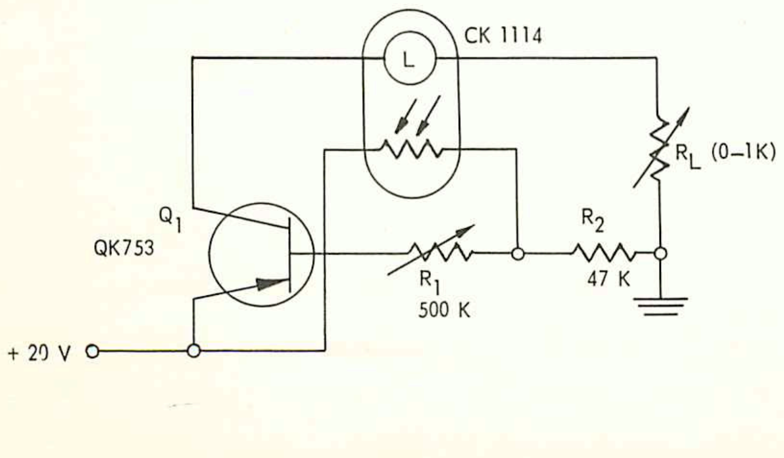
The initial control voltage applied to the Raysistor (by adjusting R2), the value of C1 and the desired range of operating frequencies are mutually interdependent. Other limitations are also imposed by the responses of the transformer T1, the demodulator and the speed limitations of the Raysistor itself.



In the schematic shown, a phase shift of 90° ± 2° was realized over the range from 200 cycles to 2,000 cycles using C_1 equal to 0.01 microfarad.

CONSTANT CURRENT REGULATOR

The Raysistor can be used as a control in a relatively simple current regulator. The control element is used to sense current changes, and the signal element is used in a simple feedback circuit as shown, forming a voltage divider with R_2.

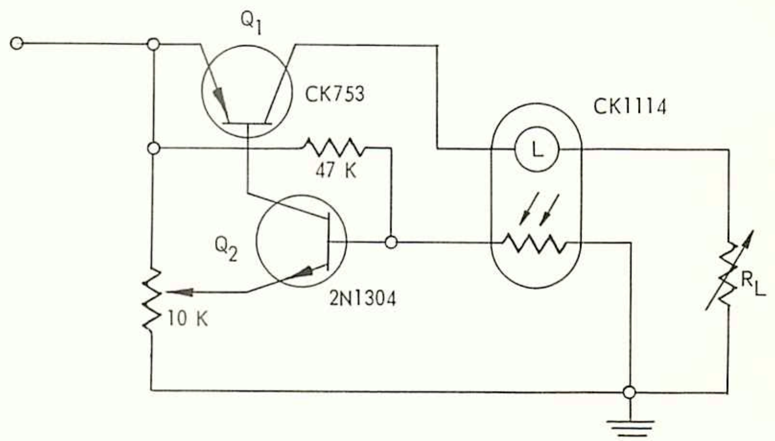


The tie-point is connected to the base of the transistor through R_1. The transistor is selected by consideration of maximum load current required and minimum load resistance.

The load current can be set to the desired value by varying R_1. Maximum load current is determined by the control current range of the Raysistor.

When the load current changes, the resistance of the Raysistor signal element changes. The resultant variation in Q_1 base current is followed by a change in the conductance of Q_1. This provides a compensation change in load current since the combined conductance of R_L and Q_1 remains constant.

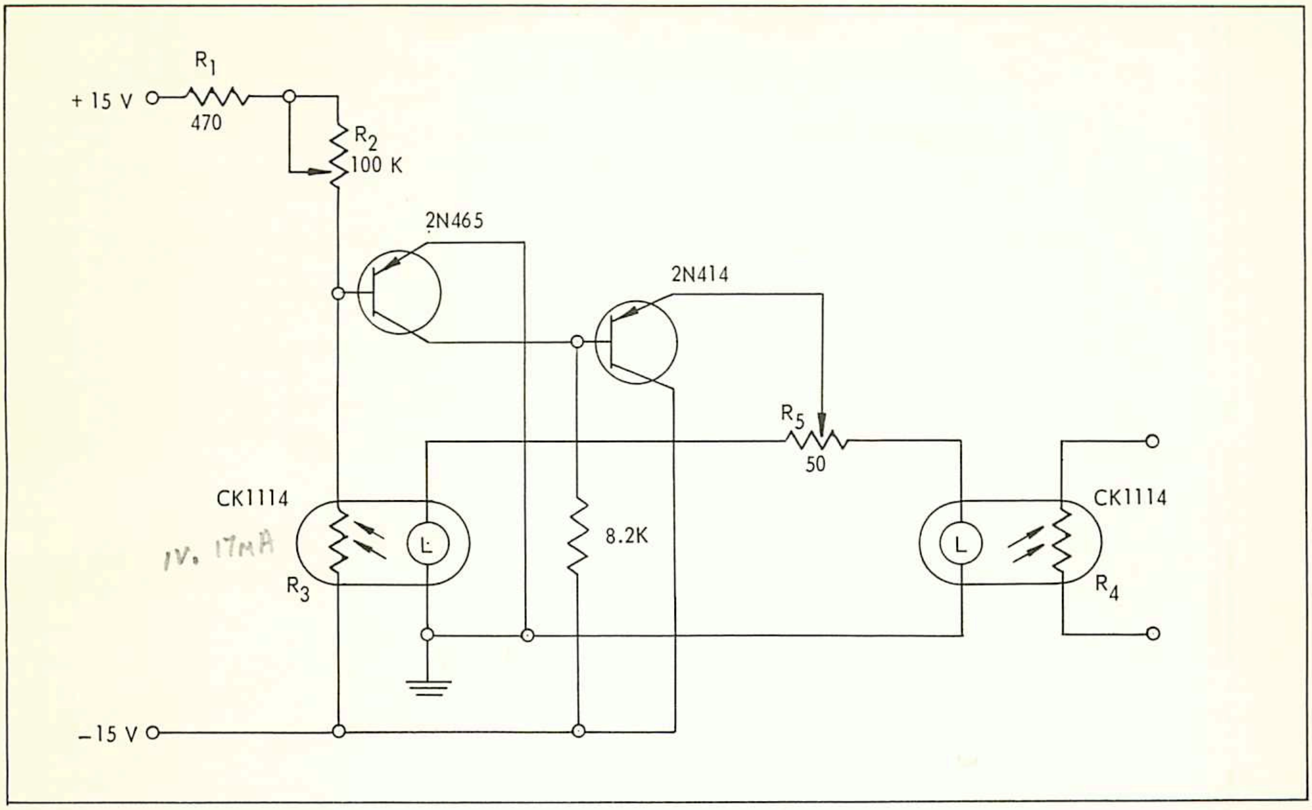
The loop gain is sufficient to keep the load current within ten per cent when R_L is varied from 0 to 1,000 ohms. Improved regulation can be achieved by adding another transistor to increase loop gain.



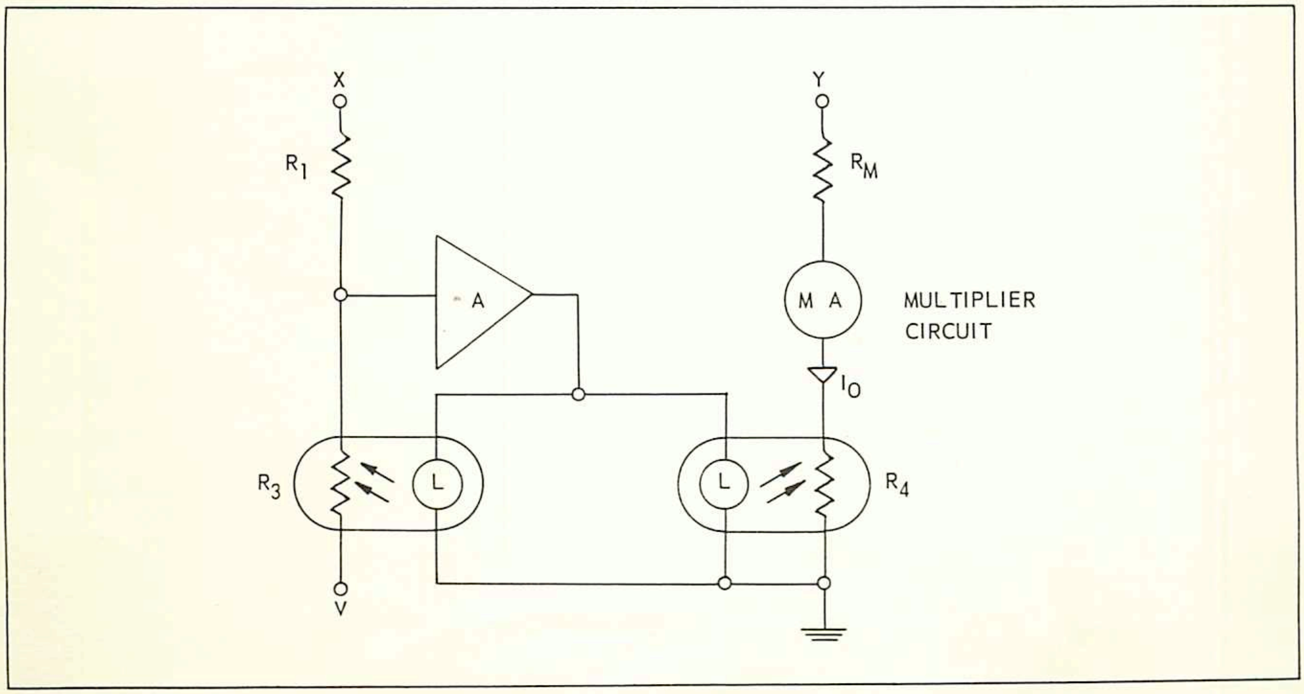
LINEAR REMOTELY-CONTROLLED POTENTIOMETER

The Raysistor can obviously be used alone to perform as a remotely controlled, non-linear potentiometer. It can also perform as a remotely controlled, linear potentiometer when used in the circuit shown.

Here R_1, R_2, and R_3 form a voltage divider between the positive and negative voltages. The null point is the input to an amplifier which drives the control of both Raysistors. The signal element (R_3) of the Raysistor is used as a reference against which the input potentiometer is compared. R_1 is chosen to match the "on" resistance of the Raysistor at nominal control voltage, thus limiting the minimum resistance in the upper arm in order to prevent overdriving the Raysistor.



R_5 is a balance control to compensate for any variations which may exist between the two Raysistors. It is set by first adjusting R_2 to some known value (e.g. such that R_1 plus R_2 equals the midpoint of the range to be covered) and then adjusting R_5 until R_4 equals the combined resistances of R_1 and R_2.



In operation, if R_3 differs in resistance from that of R_1 and R_2 an error signal appears at the input to the amplifier producing a control current in the Raysistors which corrects R_2 to equal the sum of R_1 and R_2. The output resistance (R_4) will also follow and, hence, if R2 in a linear potentiometer, R4 will vary linearly with variation in R2. In the circuit shown, R4 followed the variation in R2 within five per cent over the range of 1, 000 to 100, 000 ohms.

Note that this circuit can easily be modified to become an analog multiplier or divider. In the block diagram shown, assuming that R3 and R4 are matched, then

$$R4 = \frac{R1\ V}{X}$$

and

$$Io = \frac{XY}{R1\ V} = K1\ (XY)$$

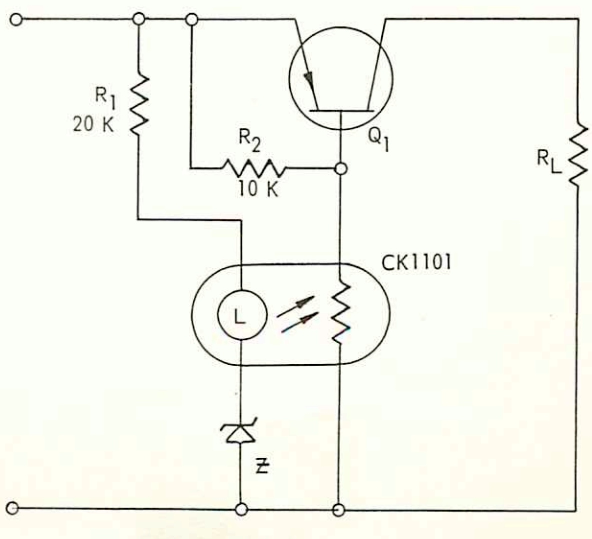
where RM $\ll$ R4, and where X and V continue to be of opposite polarity.

For a divider circuit, interchange X and V, and

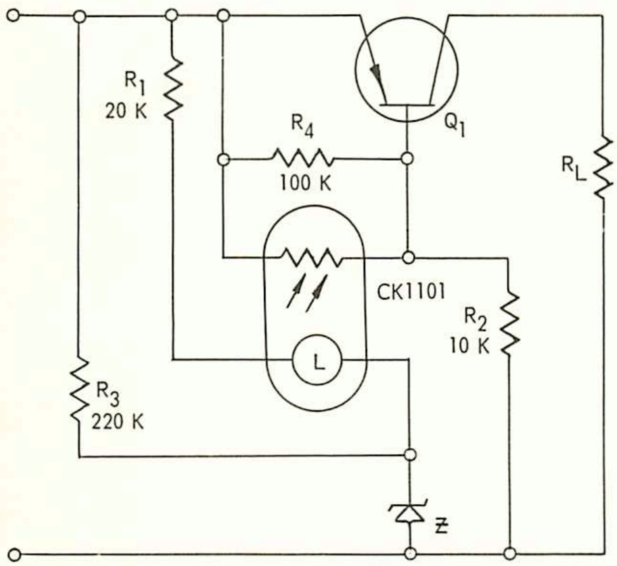
$$Io = \frac{VY}{R1\ X} = K2\ \frac{Y}{X}$$

VOLTAGE PROTECTION CIRCUITS

The Raysistor can be used as an under-voltage protection device. In the common emitter transistor circuit shown, the control lamp of the Raysistor is in series with a current limiting resistor, R1, and a Zener diode. The Raysistor signal



resistance is in series with the bias resistor R2 and the base of the transistor is driven from the junction of the two. With full voltage applied to the circuit the Raysistor control lamp fires and the signal resistance drops to a low value (< 1K), driving the transistor into saturation thus causing full current to flow.
When the supply voltage drops below some predetermined level as established by the Zener diode, the voltage across the lamp drops below the extinguishing voltage causing the signal resistance to increase rapidly to a large value (> 1 meg.). This, in turn, biases the transistor off and forces the load current to drop the I_{co} level of the transistor.



The Raysistor may also be used as an over-voltage protection device.
The circuit is similar to the previous one described except that the Raysistor signal resistor is now the biasing resistor. At low voltage levels the transistor is saturated and the full voltage appears across the load. When the voltage reaches the maximum desired level)determined by the firing voltage of the control lamp plus the Zener diode voltage), the lamp fires, the Raysistor signal resistance drops to a low level and the transistor is biased to cut-off.
In both circuits, the minimum current through the load will be the I_{co} of the transistor. The transistor is chosen with regard for the voltage used and the current to R_L.

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