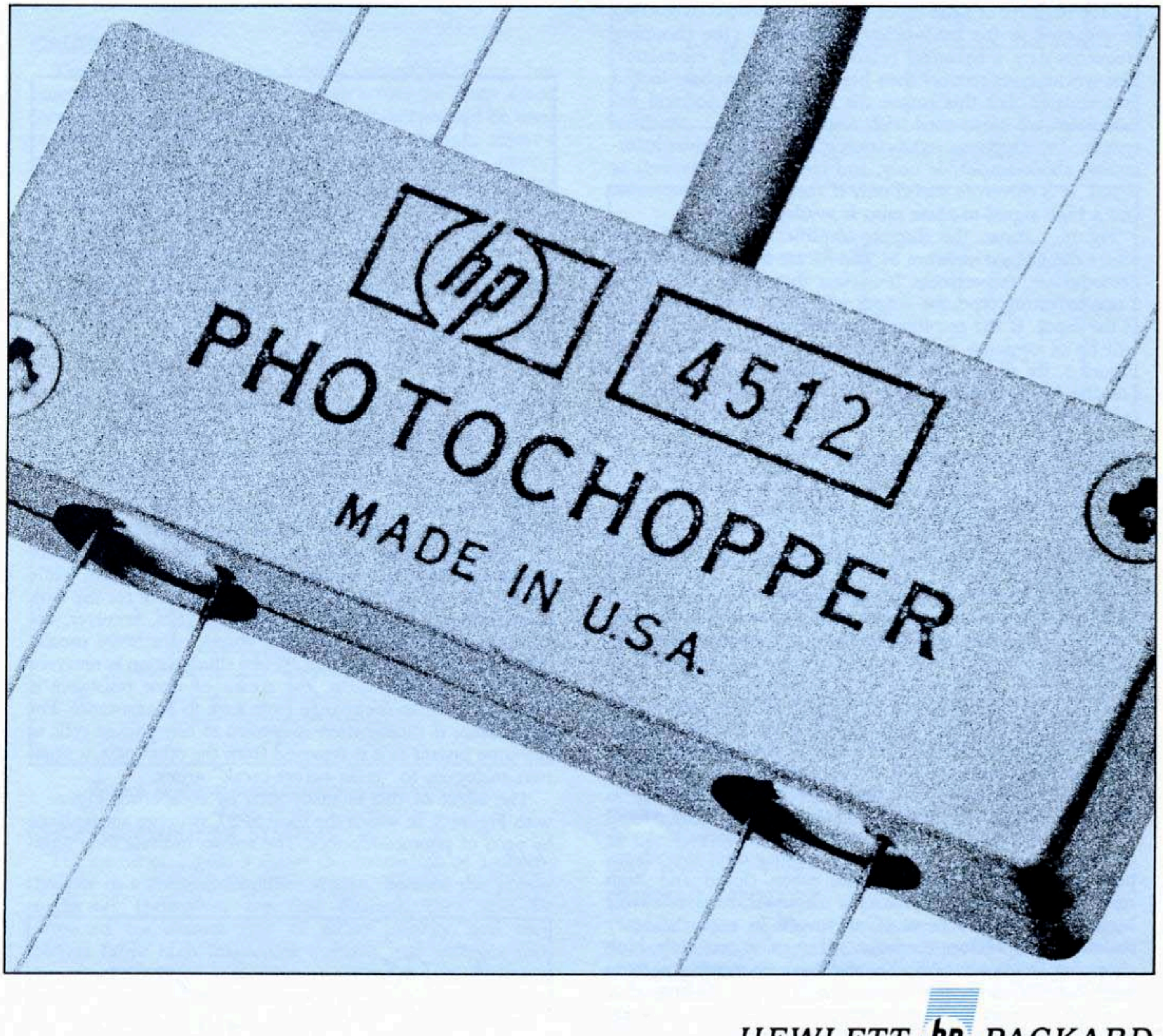
APPLICATION NOTE 911

Low Level DC Operation Using HP Photochoppers



HEWLETT PACKARD

INTRODUCTION

Photochoppers are so named because their principal application is the conversion, by chopping, of a DC or slowly varying AC input signal into a higher frequency signal. The amplitude of the resulting signal is proportional to that of the input signal, and its frequency is the chopping rate. Amplification can be performed at the chopping frequency by an AC coupled amplifier, thereby minimizing drift and noise. These benefits result because amplifier noise tends to increase inversely with frequency, and so shifting the information bandwidth upward reduces these random effects. At the output of the amplifier, the signal can be rectified, either synchronously or asynchronously, to give an output that is proportional to the input. If synchronous rectification is used, the polarity and phase of the output is the same as (or the negative of) the input. The system may conveniently be regarded as the modulation of a carrier (the chopping frequency) by a balanced (carrier suppressed) modulator. The synchronous rectifier then has the role of a phase-locked demodulator. For this reason the terms modulator and demodulator are often used with respect to chopper-amplifier system. Asynchronous rectification of the output gives information about amplitude only, and rectifies noise as well as signal. It is therefore useful only if feedback is unimportant and a high signal-to-noise ratio is available.

Figure 1 shows the chopper-amplifier in idealized form where the ganged switches S1 and S2 are the modulator and demodulator, respectively. It is clear that if the amplifier is a non-inverting type, the output will have the same polarity as the input. If the amplifier is an inverting type, the output will be of opposite polarity if connections are as given in Figure 1. By simply reversing the output connections of S2 (or the input connections of S1) the inverting amplifier can yield an output of the same polarity as the input.

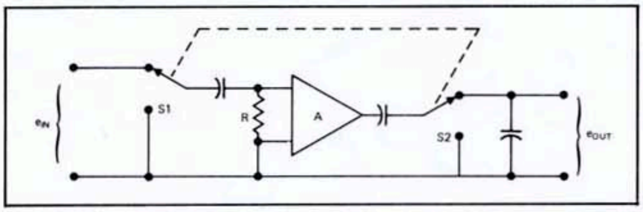


Figure 1. Idealized chopper-amplifier

With respect to the basic concept of chopper action, any device or collection of devices which performs the function of a single-pole double-throw switch is applicable. This would, therefore, include mechanically and electrically driven switches, transistors (either monopolar or bipolar), and photochoppers. Switches suffer from the noisy effects of contact bounce and wear, thermocouple offsets, and vulnerability to vibration and shock, but they offer the advantage of extremely low resistance when closed and high resistance when open. Transistor choppers have relatively high offset voltages (tens of microvolts in even the best) and high temperature coefficients, but offer extremely high chopping frequency capability and have no moving parts to wear out. Photochoppers are best with respect to low offset and drift, and in most applications these considerations are of primary importance. Moreover, with the use of electrically modulated light (neon lamps) rather than mechanical interruption to obtain the chopping frequency, moving parts have been eliminated. For these reasons, photochoppers should be given first consideration when extremely low level (nanovolts) signals must be chopped, or when operation in environments of high vibration or wide temperature excursions (0-65°C) are encountered.

DEVICE DESCRIPTION

Since the data sheets give detailed information concerning the structure and characteristics of HP photochoppers, only the essential nature of the device is described here. The photochopper consists of four photoconductors so arranged that one pair is illuminated by one neon lamp and the other pair by another lamp. The schematic diagram of this arrangement is shown in Figure 2. When illuminated by their respective neon lamps, the photoconductors rapidly attain a conductance which is several decades greater than their conductance when dark.

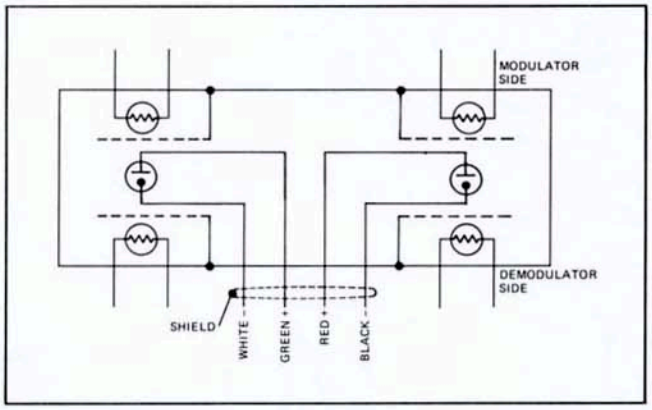


Figure 2. Schematic diagram of photochopper

The resistance when lit is determined by the intensity of illumination and the pattern of the photoconductor. The HP 5082-4511's are made to have a high input resistance modulator for operation with high impedance circuits, while the HP 5082-4512's have lower input resistance for use with lower impedance circuits. Demodulator cells, however, are the same in both types, since the output circuits are usually much more flexible in design. When illumination is removed from the photoconductor, the return of dark resistance is much slower than the change from dark-to-lit resistance. For this reason, if illumination is applied to one pair of cells at the same instant as it is removed from the other pair, a situation analogous to "make-before-break" arises.

The effect of this is easily seen by comparing Figure 1 with Figure 3, in which the ideal SPST switches are replaced by pairs of photoconductors. The arrows indicate the illumi-

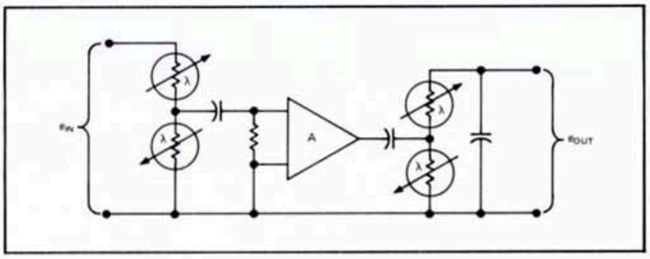


Figure 3. Schematic diagram of photochopper amplifier

nation phase. By introducing a short period of time between removing illumination from one pair and applying it to the other, time is allowed for the lit-to-dark-resistance transient to get a good start before the other pair is illuminated. The illumination "dark time" is beneficial in both the demodulator and the modulator ends of the chopper amplifier. The appropriate length of dark time varies according to the circuit environment of the chopper, chopping frequency, and lit resistance of the photocell. Therefore, no specific illumination dark time is recommended as being best. The general rule is that a short or zero dark time reduces input resistance, a long dark time raises the output resistance, possibly lowering efficiency. The best operating compromise is typically between 0.5 and 1.5 milliseconds. This dark time can be expressed as a percentage of the illumination—30% at 200 Hz corresponds to 0.75 millisecond.

CAUTION

The neon lamp requires a high voltage for firing, but immediately upon firing the voltage across the lamp drops forty volts or more. At least 75 K resistance should be used in series with the lamp. Figure 4 shows the voltage across a neon lamp driven from a combined AC and DC source. Firing and maintaining voltages are clearly indicated. Notice that the source voltage must be reduced below the maintaining voltage before the lamp will extinguish. Lamp drive circuits will be discussed later in greater detail.

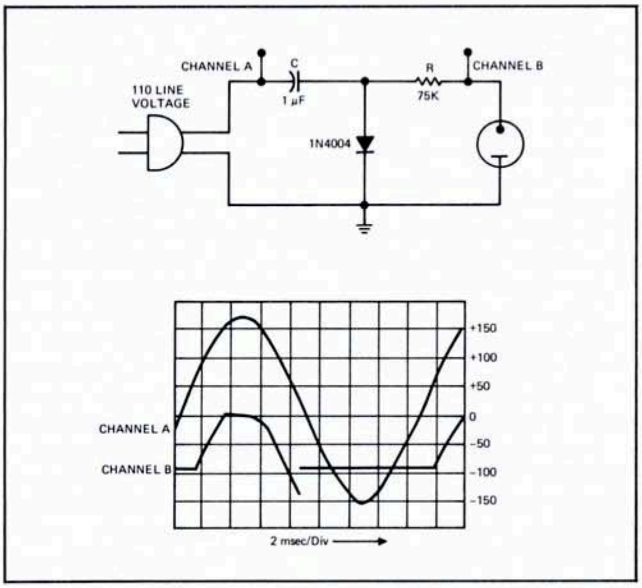


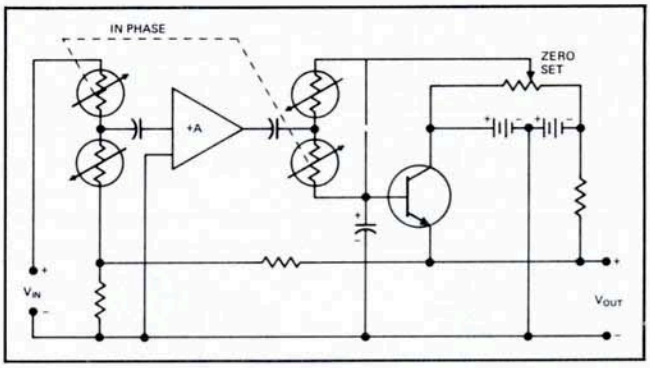
Figure 4. Neon lamp excitation characteristics

CHOPPER-AMPLIFIER SYSTEMS

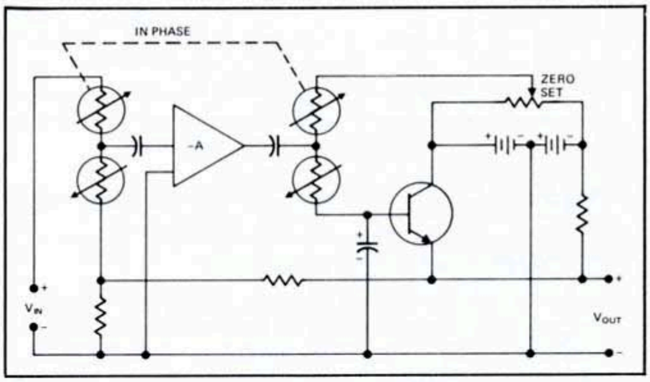
The circuit of Figure 3 shows the connection of a photochopper in a chopper-amplifier system. Because the photoconductors themselves are free floating, they may be connected for current flow of either polarity, and they tolerate fairly high magnitude currents and voltages (see data sheet for maximum ratings). As shown in Figure 3, the chopper-amplifier represents a DC amplifier capable of extremely high gain and low drift—an ideal operational amplifier. The feedback techniques applied to operational amplifiers are therefore appropriate.

VOLTAGE FEEDBACK CIRCUITS

Two possible examples of output stage connections for voltage feedback are shown in Figure 5. In this mode the modulator photocells are operating between the input voltage and the feedback voltage, which raises the input resistance to the product of the modulator input resistance and the loop gain. Stabilizing the loop is not difficult, since it typically has one-pole response all the way down the unity loop gain crossover frequency produced by the demodulator output resistance and the output filter capacitor.



a) With non-inverting amplifier



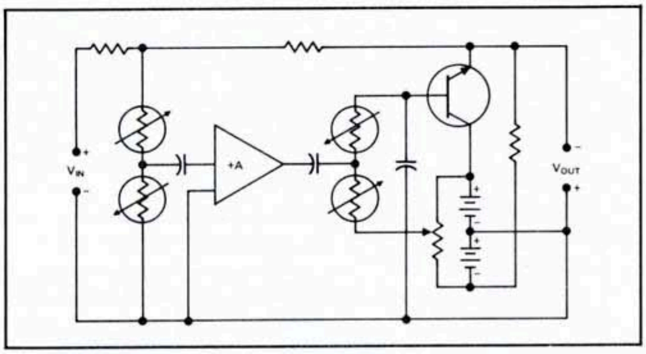
b) With inverting amplifier

Figure 5. Voltage feedback with photochopper amplifier

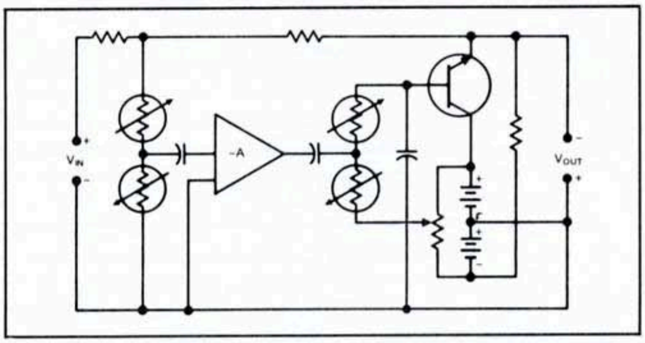
An interesting problem may come up, however, if the amplifier is a non-inverting type. During the illumination cycle there is bound to be an instant during which the resistance of the series photocell is approximately equal to the resistance of the shunt photocell. If this resistive overlap occurs at the same time at both input and output, there is a brief moment of positive feedback with a loop gain only about 12 dB less than normal, and this may allow a high enough gain to cause sharp impulses to appear at the cyclic moment of resistive overlap. The effect can be puzzling since the usual system design procedure regards the chopper-amplifier as simply a low-drift DC amplifier. Adding a filter or another stage of amplification will correct this condition.

CURRENT FEEDBACK

Examination of Figure 6 shows that the output circuit biasing techniques are the same. The difference between voltage and current feedback is mainly that the input resistance of the amplifier with current feedback is the modulator input resistance *divided* (rather than multiplied) by loop gain. Also the resistive overlap impulses can occur if the amplifier is non-inverting, rather than inverting. Other advantages of negative feedback are thoroughly discussed in literature on operational amplifiers. The examples given here are mainly for the purpose of illustrating the circuit design freedom offered by photoconductors.



a) With non-inverting amplifier



b) With inverting amplifier

Figure 6. Current feedback with photochopper amplifier

CHOPPER-STABILIZED AMPLIFIER

As mentioned previously, the chopping frequency of chopper-amplifiers is analogous to a carrier, and the modulation bandwidth is obviously limited to something less than the carrier (chopping) frequency. In typical designs, the bandwidth is deliberately limited by the demodulator in order to prevent inclusion in the passband of those lower frequencies at which flicker noise dominates. When broadband response is required along with the extremely low drift of the chopper amplifier, a combination of AC and DC amplifiers is used. Such a combination, illustrated in Figure 7, is called a chopper-stabilized amplifier. The low frequency roll-off of the AC amplifier is adjusted to match the high frequency cutoff of the DC chopper amplifier, and negative feedback takes care of imperfections in adjustment so that the overall response is constant from several megacycles right down to DC.

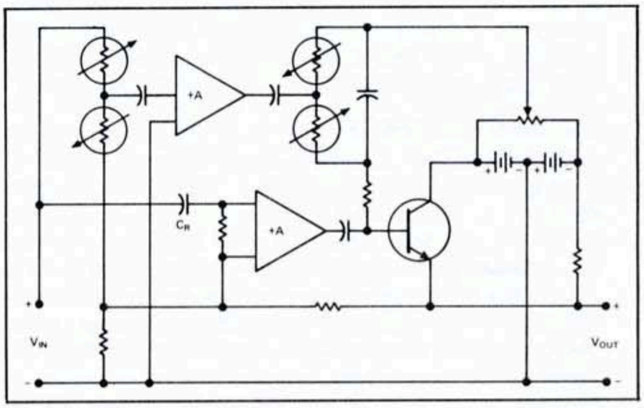


Figure 7. Chopper-stabilized amplifier system

NOISE LIMITATION IMPOSED ON AMPLIFIER GAIN

With drift and 1/f noise essentially eliminated from the output, the designer may be tempted to design the AC amplifier with higher gain than the system can handle. Although the modulator/demodulator system prevents low frequency noise from appearing in the output, it may still be present in the amplifier. If the AC gain is made too high, relative to amplifier noise and amplitude capability, the final stage may be saturated by noise and therefore incapable of responding to the chopped signal, no matter how large it is. Certainly threshold signals would be submerged beyond recovery. One possible procedure for controlling the situation is the use of bandpass filters in the AC amplifier. This requires attention to the proper adjustment of the phase shift at the chopping frequency in order to obtain efficient synchronous demodulation, but has the advantage of helping to prevent the "resistive-overlap positive feedback." Another possible method of preventing noise saturation of the amplifier is to discover and reduce the sources of noise, which may be either synchronous or asynchronous noise. Examples of asynchronous noise would be flicker and shot noise in the amplifier devices, or stray AC signals coupled into the low-level stages; e.g., power supply ripple is asynchronous if the chopping frequency is something other than 60 Hz.

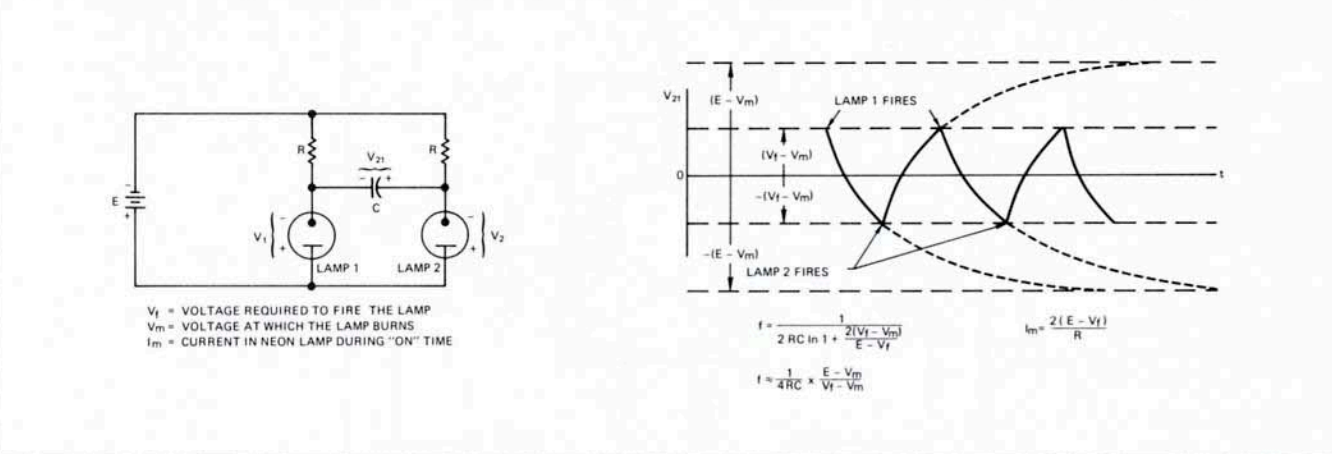
Examples of synchronous noise are DC offsets due to thermocouples or chemically generated stray DC voltages at the input. When chopped these signals produce synchronous AC signals. If the neon lamps are driven at line frequency any extraneous signals coupled in at the line frequency must be regarded as synchronous noise. In some cases, such as when the synchronous noise is produced by a DC at the input, its effect can be eliminated by introducing DC of equal magnitude but opposite polarity. Synchronous noise which is introduced as an AC signal in the amplifier may not have the right relative phase to be completely balanced out by insertion of a DC signal at the input, and unless it is eliminated by coupling in another signal of equal amplitude and opposite phase, it could impose a limit on the gain, the threshold sensitivity, or both. One example of such a noise source is the AC voltage applied to the neon lamps, a fraction of which might be coupled through to the amplifier. As a means of preventing this, HPA photochoppers are made with photocells whose glass lenses are coated with a conducting film to shield the photoconductor from the electrical transients present at the neon lamp's terminals. The benefit of the photocell shield is lost, however, unless the circuit layout for the neon lamps is carefully arranged to avoid such coupling outside the photochopper case. The braided shield over the neon lamp connecting wires is helpful in achieving such a layout.

NEON LAMP DRIVE CIRCUITS

Of the many possible drive circuits for cyclically operating the neon lamps, only a few examples will be given. These should suffice to illustrate the practical techniques.

TWO-LAMP RELAXATION OSCILLATOR

This circuit, shown in Figure 8, is the simplest and most widely used method of driving these lamps. Analysis of the circuit proceeds from the equivalent circuit representation of the neon lamp as an open circuit until firing voltage is reached at V_f, and as a voltage source of V_m while it is lit. Begin by assuming that lamp 1 is about to ignite, so $V_1 = V_f$ and lamp 2 is burning, so $V_2 = V_m$. The voltage on the capacitor must satisfy Kirchhoff's Law for the sum of voltages around the loop, and must therefore be $V_{21} = V_f - V_m$. When lamp 1 does ignite, V_1 drops immediately to



V_f = VOLTAGE REQUIRED TO FIRE THE LAMP
V_m = VOLTAGE AT WHICH THE LAMP BURNS
I_m = CURRENT IN NEON LAMP DURING "ON" TIME

$$f = \frac{1}{2\,RC\ln 1 + \frac{2(V_f - V_m)}{E - V_f}}$$

$$I_m = \frac{2(E - V_f)}{R}$$

$$f \approx \frac{1}{4RC} \times \frac{E - V_m}{V_f - V_m}$$

Figure 8. Two-lamp relaxation oscillator

V_m and this voltage drop, coupled through the capacitor, will turn lamp 2 off, and there now ensues a linear transient as the voltage on the capacitor changes polarity, moving with a time constant, RC, toward an asymptote—$(E-V_m)$. Solving the linear transient formula for the time required for V_{21} to reach the voltage at which lamp 2 fires, yields the result given in Figure 8 for the chopping frequency. The waveform of the voltage on the capacitor is also shown, along with the asymptotes and intersections that produce it. From these it is clear that a high (with respect to V_m) value of E is desirable to obtain stable operation.

DIRECT POWER-LINE DRIVE

In some applications it is desirable to operate the neon lamps directly from the power line. The neon lamps in the HP 5082-4511 and 5082-4512 are provided with a four-conductor shielded cable for making external connections. Since the neon lamps become polarized after some hours of operation, it is imperative that lead arrangements for driving the lamps be consistently the same throughout the life of the lamp to provide the proper lamp polarity. One possible arrangement is shown in Figure 9. Operation of the circuit is most easily understood when analysis is based on the direction of current flow rather than on the polarity of the applied voltage. When loop current is in the direction shown, one path is via C1 and D1 charging C1 to the peak value of the line voltage; another path is R1, lamp 2, R4, and C2; the third path, through R1 and R2 is not especially significant, except that the resistors R1 and R2 provide current paths and divide the line voltage for application to the neon lamps. Ignition of lamp 2 takes place just before the peak position swing of V, at a point determined by the amount of charge on C2 from the previous negative half-cycle. Lamp 2 in burning quickly draws a quantity of charge from C2 and thereafter there are no transients, but simply the line-voltage controlled (from drop across R2) satisfaction of Kirchhoff's Law for the loop R2, lamp 2, R4, and C2. Therefore, the amount of current flowing in lamp 2 is just the amount of current necessary to produce the rate of change of voltage on C2 to equal the rate of change of voltage on R2, and hence the "ON" current is selected by choosing the value of the series capacitor. The illumination duty cycle always ends at the point in the cycle when the current reverses, and the duration is therefore determined by the cyclic position at which the lamp ignites. This can be regulated to some extent by adjusting the voltage to which the capacitors are charged during their respective lamp "OFF" times, and this, in turn, is adjusted by tapping the cathode ends of the diodes D1 and D2 down on the line-driven resistors R2 and R1, respectively. However, with the circuit connected as shown and with the values given, the lamps receive 2.2 mA while on and provide almost 1.0 millisecond of dark time when driven at 60 Hz. This is very near the optimum dark time of 0.8 millisecond.

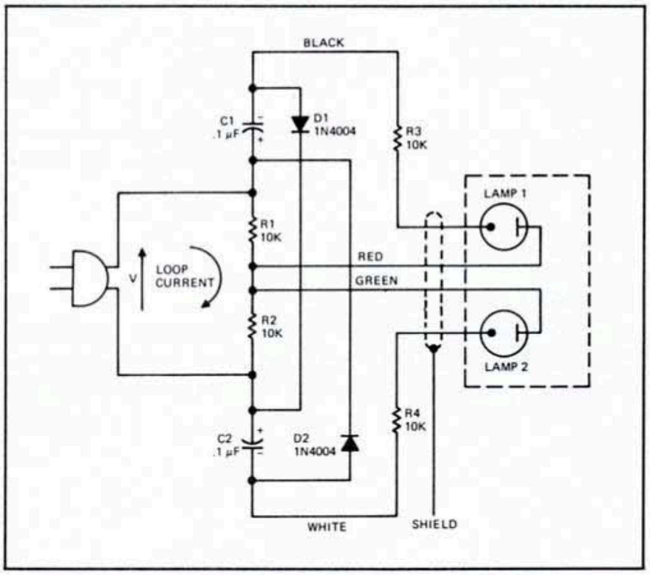


Figure 9. Direct line neon drive

ASTABLE MULTIVIBRATOR CIRCUIT

The circuit shown in Figure 10 is an astable multivibrator driving the neon lamps with transistors Q1 and Q2. This circuit provides a drive signal of 100 Hz and provides dark time of about 0.8 millisecond between the lit states of the neon lamps. R1 can be used to adjust the frequency approximately 10% and the frequency range can be varied by changing R4 and R5, or C1 and C2. The dark time can be varied by changing C3 and C4.

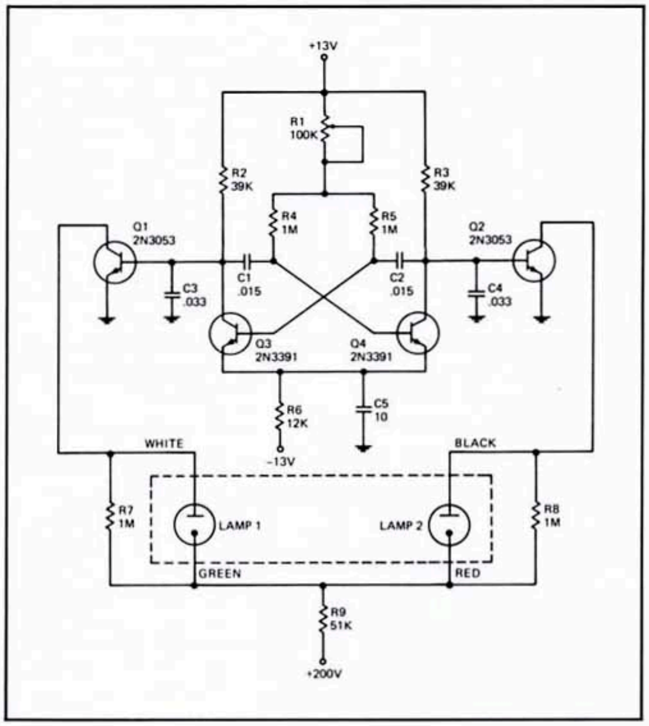


Figure 10. Transistor-driven lamp circuit

SUMMARY

The fundamental features of HP 5082-4511 and 5082-4512 photochoppers have been described and suggestions have been made as to how these features can be employed to obtain the utmost in low-level DC signal processing. A few methods of producing the required illumination cycles have also been discussed.