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OPTIMIZING SIGNAL-TO-NOISE RATIO IN PHOTOCHOPPER APPLICATIONS

620 Page Mill Road, Palo Alto, California, U.S.A., Cable "HEWPACK" Tel. (415) 321-8510

Europe: 54 Route Des Acacias, Geneva, Switzerland, Cable: "HEWPACKSA" Tel. (022) 42.81.50

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CHOPPER AMPLIFIER OPTIMIZATION

USING PHOTOCONDUCTOR CHOPPERS

There are several specialized considerations in making the design selections for optimizing a photochopper amplifier. The purpose of this application note is to describe these considerations, develop the rules for making the design selections, and illustrate these rules with typical values. The note also discusses the construction of photoconductive cells (photocells) to show how the first steps toward optimization must be taken by the photocell manufacturer.

It is presumed that the designer already knows that the chief advantage of a photochopper over other types of choppers is its high signal-to-noise ratio capability. For this reason optimization of the signal-to-noise ratio will be regarded as the primary objective. There are, of course, other design considerations, such as cost, size, weight, tolerance of environmental conditions, and ruggedness. These will be discussed only to the extent that photochoppers present special situations.

PHOTOCELL CONSTRUCTION

Although there are many materials which exhibit a response to optical excitation, only two basic types are commercially suitable for photoconductor construction. These are cadmium sulfide (CdS) and cadmium selenide (CdSe). Cadmium sulfide has higher sensitivity to optical signals and lower temperature coefficient of resistance than cadmium selenide; unfortunately it is also slower, by as much as one or two orders magnitude, in its conduction decay transient (changing from lit resistance to dark resistance). As will be shown later, cell speed is very important in photochopper applications, and cadmium selenide photocells are sometimes favored despite their lower sensitivity and higher temperature coefficient.

Hewlett-Packard uses a technique which combines these two materials to obtain cadmium sulfo-selenide. By adjusting the sulfide-to-selenide ratio, device performance has been optimized with respect to typically realizable circuit conditions. That is, as much as possible of the desirable cadmium sulfide sensitivity and thermal stability is retained, consistent with the speed required for circumventing the low frequency noise and drift of a typical amplifier. Another advantage is that cadmium sulfo-selenide has a response in the optical spectrum which peaks at a wavelength between the peaks obtained with pure cadmium sulfide and pure cadmium selenide. This modified peak just happens to be the most efficient match for radiation from a neon lamp, which is a popular source of illumination for photoconductor choppers.

Selecting the proper sulfide-to-selenide ratio is only the beginning in a series of treatments designed to optimize the photoconductive material for both speed and stability. However, the details of these treatments are beyond the scope of this note. The resulting material, under light conditions standard at Hewlett-Packard (600 μwatt per cm^2 at 6550Å), has a resistance of about one megohm per square. While such a level of lit resistance is suitable for use with tube and field effect transistor circuits, it is much too high for other applications. Lower values of lit resistance are obtained by use of an interdigitated contact pattern which connects anywhere from ten to more than one hundred of these squares in parallel, thus providing lit resistances with practical values.

Another design selection made by the manufacturer of the photocell is the contact material. Metals having work functions which differ from that of the doped cadmium sulfoselenide will produce photovoltaic effects. In applications requiring only an external indication of the presence or absence of light, photovoltaic effects can often be neglected; but in photochopper applications they are disastrous. Photovoltaic effects appear externally in either (or both) of two ways:

1. Under steady light a steady dc voltage appears at the photocell terminals. Ideally a photoconductor exhibits no extraneous voltage, but simply changes resistance in response to illumination.

2. In response to fluctuating light there appears a fluctuating photovoltage. Although it vanishes when illumination is steady, this voltage can be synchronously rectified by the photo-responsive conductivity fluctuations, thereby causing a dc voltage to appear at the photocell terminals.

In poorly constructed photocells the combined photovoltaic effects may be more than a microvolt, which seriously limits the minimum detectable signal in chopper applications. Transient photovoltaic effects appear to some extent in even the best of photocells, but in most cases they become troublesome only if very high rates of cyclic illumination are applied, and even then the effect is greatly reduced by proper circuit design. More will be said about this in the discussion of circuit design.

Choice of photocell packaging materials is also critical, especially when photochopper applications are considered.

First, the package must be electrostatically shielded. Evaporating a thin gold film on the glass window of the package is a fairly common practice, but it is not always effective. A common fault is the appearance of microscopic cracks in the gold film where the glass meets the metal. This breach of electric integrity permits coupling of ac signals at the chopping frequency from the cyclic voltage applied to the source of illumination. This could be circumvented by mechanical, rather than electrical, modulation of the illumination, but it is much better to use photocells which are packaged with a consistently careful control of quality in choice of materials and the way they are used.

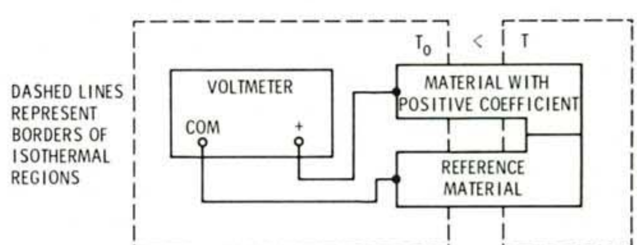
The material selected for the photocell leads could be critical, depending upon where and how the photochopper is used. In isothermal environments the lead material has no electrical significance. Only when a thermal gradient exists does the lead material become electrically important. The designer is in a better position than the photocell manufacturer to judge the magnitude of thermal gradient. Hewlett-Packard supplies all photocells with dumet leads, but makes OFHC copper leads available, at additional cost, for applications where significant thermal gradients exist. As a guide to making proper judgment, the following table is offered.

Table 1. Thermal EMF Coefficients*

Material	Thermal Coefficient in μV/°C Relative to Platinum	Thermal Coefficient in μV/°C Relative to Copper	Material	Thermal Coefficient in μV/°C Relative to Platinum	Thermal Coefficient in μV/°C Relative to Copper
Elements			**Alloys**		
Copper	+7.6	±00.00	Manganin	+6.1	−1.5
Cadmium	+9.0	+1.4	Gold-chromium	−1.7	−9.3
Aluminum	+4.2	−3.4	Beryllium Copper	+6.7	−0.9
Indium	+6.9	−0.7	Brass, yellow	+6.0	−1.6
Mercury	−6.0	−13.6	Phosphor bronze	+5.5	−2.1
Magnesium	+4.4	−3.2	Solder 50 Sn 50 Pb	+4.6	−3.0
Zinc	+7.6	−0.0	Solder 96.5 Sn 3.5 Ag	+4.5	−3.1
Carbon	+7.0	−0.6	Stainless steel, 18–8	+4.4	−3.2
Germanium	+339.0	+331.4	Spring steel	+13.2	+5.6
Silicon	−415.6	−423.2	Nichrome 80 Ni, 20 Cr	+11.4	+3.8
Tin	+4.2	−3.4	60 Ni, 24 Fe, 16 Cr	+8.5	+0.9
Lead	+4.4	−3.2	Copper coin 95Cu 4 Sn 1 Zn	+6.0	−1.6
Gold	+7.8	+0.2	Nickel coin 75 Cu 25 Ni	−27.6	−35.2
Silver	+7.4	−0.2	Silver coin 90 Ag 10 Cu	+8.0	+0.4
Nickel	−14.8	−22.4	**Other Materials**		
Iron	+18.9	+11.3	†Nickel-Iron component lead	−26.4	−34.0
Palladium	−5.7	−13.3	†Dumet component lead	−6.4	−14.0
Molybdenum	+14.5	+6.9			
Tantalum	+3.3	−4.3			
Tungsten	+11.2	+3.6			

*Data taken from American Institute of Physics Handbook, 2nd Ed., pages 4-7 through 4-11. Although table values are in μV with respect to platinum only, the figures with respect to any other material can be obtained by subtracting the coefficient of that material with respect to platinum. Signs, + or −, must be given in order to describe the polarity of the thermocouple voltage. The diagram shown describes how polarity is defined; for $T > T_o$, the voltmeter will show a positive indication if the material under test has a positive coefficient with respect to the reference material.

†Measured value — not from handbook.



SELECTING THE PHOTOCELL

Characteristics of stability with respect to time, temperature, and other environmental conditions are established by the manufacturing process for the photocell. These characteristics are therefore not a matter of design selection. Only two parameters remain to be chosen: lit resistance and recovery speed. The effects of these two parameters on system performance are examined in two steps:

1. Effects of photochopper parameters on the overall chopper amplifier system.

2. Effects of photocell lit resistance and recovery speed on photochopper parameters.

Photochopper Parameters

Three parameters must be considered for a photomodulator: input resistance, output resistance, and modulation efficiency, with special attention to how they vary with chopping (modulation) frequency. Although there is interaction among them, with possible tradeoffs, the range of desirable limits can be defined separately for each parameter.

Input resistance should be as high as possible, since it establishes the input resistance of the chopper amplifier system. However, it is possible that performance specifications demand a higher value of input resistance than is consistent with optimizing signal-to-noise ratio. Considerations of signal source loading or high precision may, in some cases, take precedence over optimizing the signal-to-noise ratio; where this is true, a designer might do better with some other kind of chopper. Such a comparison is beyond the scope of this discussion, however, and with respect to signal-to-noise ratio, all that can be done for input resistance is to make it as high as possible.

Output resistance has a definite optimum value. It should be high, due to its relationship to input resistance (via lit resistance of the photocell), but there is an upper limit. Since the output resistance of the photochopper represents the source resistance for the amplifier, the upper limit on its value is established by the noise properties of the amplifier. Typically, the noise properties of an amplifier can be represented by a noise voltage e_A in series with the amplifier input, and a noise current i_A in shunt. The equivalent circuit of this representation is shown in Figure 1.

Since noise is not coherent, noise components cannot be summed linearly, but the sum of squares will correctly yield the square of the rms equivalent voltage. Referring to the equivalent circuit in Figure 1, the squares of the noise components at the input terminals are:

$$e_A^2,$$

which is simply the square of the short circuit noise voltage

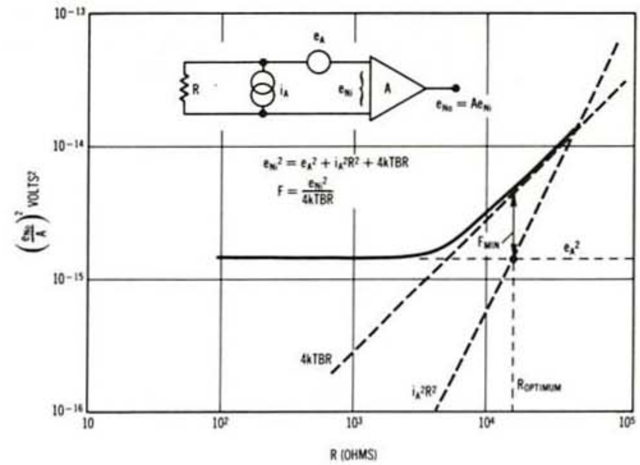


Figure 1. Square of Amplifier Noise Voltage as a Function of Signal Source Resistance

$$i_A^2R^2,$$

which is the square of the noise voltage produced by the noise current, i_A, flowing in the resistance, R, and

$$4kTBR,$$

the thermal noise voltage from R, where k is Boltzman's constant, 6.25 x 10^{-23} joule/°K, T is absolute temperature in degrees Kelvin, and B is bandwidth of the system in Hertz (sec^{-1}).

The sum of these components then gives the square of the noise voltage at the input terminals:

$$e_{Ni}^2 = e_A^2 + i_A^2R^2 + 4kTBR \qquad (1)$$

Notice that the short-circuit noise voltage contribution has zero slope, while the thermal noise contribution has a slope of one and the noise current has a slope of two. These contributions can be represented as asymptotes of the total noise curve, as indicated by the dotted lines in Figure 1. These dotted lines are the asymptotes of the measured curve, obtained by measuring output noise voltage e_{NO} and voltage gain A, then plotting the square of the ratio, which is the voltage present at the input terminals. In the absence of signal, the equivalent input voltage is just the equivalent noise voltage.

Thermal noise is the absolute minimum noise. It is always present, and can be reduced only by reducing the temperature. The contributions from e_A and i_A therefore represent excess noise, and tend to degrade the signal-to-noise ratio. A figure of merit for the input can be expressed as the ratio of the square of the total noise to the square of the thermal noise of the source resistance. In fact, this ratio has common usage and is called the noise factor F. It is related to another commonly used figure of merit, the noise figure, NF as follows:

$$NF = 10 \log_{10} F . \quad (2)$$

In terms of the symbols used in Figure 1, F may be expressed:

$$F = \frac{e_{Ni}^2}{4kTBR} . \quad (3)$$

It is clear that F should be minimized, and the variable with respect to which we seek the minimum is the source resistance R. Applying the standard analytical procedure of differentiating F with respect to R, and setting the differential equal to zero, the result is

$$R_{OPTIMUM} = \frac{e_A}{i_A} \quad (4)$$

(for e_{Ni} as defined in Equation (1)). The same result is obtained graphically from a curve such as that given in Figure 1 by extending the low-R and high-R asymptotes until they intersect. The value of R at this intersection is the resistance which gives the lowest noise figure for the system. It should be noted that this is true even though the thermal noise asymptote may pass below the point of intersection (rather than above, as in Figure 1). The only significance of its passing above the high- and low-R asymptote intersection is that the minimum noise figure is less than 3dB. If it passes through, noise figure is exactly 3dB, and if below, noise figure is greater than 3dB; but this is still the minimum possible noise figure for the amplifier being characterized.

The plot of equivalent input noise voltage as a function of source resistance (Figure 1) may be a function of the frequency about which the measurement bandwidth is centered. However, flicker noise tends to affect both e_A and i_A, so that the intersection of the asymptotes has little tendency to cause the value of $R_{OPTIMUM}$ to change with measuring frequency, even though the minimum value of noise figure will be different. As a precaution against being too far off, though, the frequency of the band center at which the plot is made should be near the anticipated chopping frequency. A fair guess at the chopping frequency can be made on the basis of considerations to be discussed later.

Since the photochopper output resistance is the source resistance for the amplifier, it should have the value obtained by the asymptote intersection procedure illustrated in Figure 1.

The third photochopper parameter, chopping efficiency, has a requirement similar to that of input resistance. That is, it should be as high as possible. It is also important that the chopping efficiency cutoff frequency be high. Fortunately there is no tradeoff here; the same design choices which raise the chopping efficiency also raise the cutoff frequency. There is a tradeoff with output resistance only if the optimum value required by the procedure in Figure 1 happens to be much lower than is possible with available photocell technology and expected level of illumination. However, the range of values presently available make this extremely unlikely.

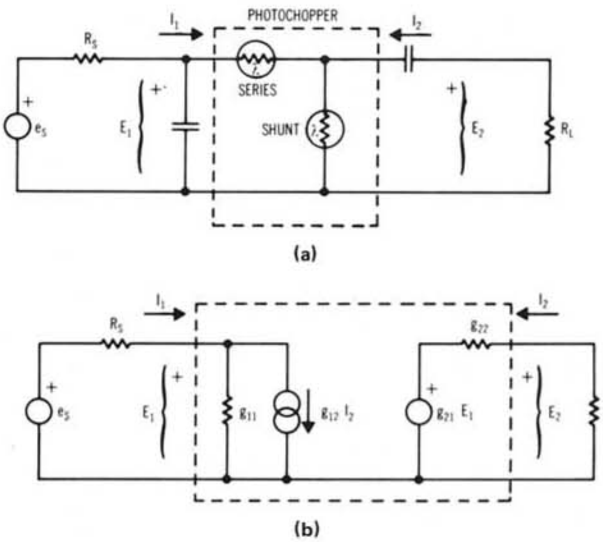


**Figure 2. Photochopper in Modulator Connection.
a. Schematic Diagram of Representation for Hybrid g-Parameters. b. Equivalent Circuit for Hybrid g-Parameters.**

Effects of Lit Resistance and Recovery Speed

The effects of photocell lit resistance and recovery speed on the photochopper parameters can be analyzed by treating the chopper as a two-port network and applying standard network theory to establish the relationships. Figure 2 shows a two-cell half-wave photochopper, with voltages and currents at the input and output labelled in the customary manner for two-port network analysis. Notice especially that the output current is shown flowing *into* the "hot" side. This is done in order to conform to the two-port network theory sign convention, even though there is a priori knowledge concerning actual input-output polarity relationships. Attention is drawn to this apparent polarity reversal now, so that there will be no confusion later when a minus sign appears in the results.

For analysis of two-port networks, the parametric coefficients relating the variables are often selected to yield dimensional compatibility with the physical realities represented by the network. In the case of transistor performance analysis it is usually convenient to use the hybrid "h-parameters".

Similarly, it is most natural to select the hybrid "g-parameters" for representing the photomodulator circuit. This selection leads to the equivalent circuit representation shown in Figure 2(b) of the network equations:

$$I_1 = g_{11} E_1 + g_{12} I_2 \tag{5}$$

and

$$E_2 = g_{21} E_1 + g_{22} I_2 \tag{6}$$

As mentioned previously, three quantities must be derived: input resistance, output resistance, and efficiency. In terms of the network parameters, the general solutions for these quantities are:

Input resistance

$$R_i = \frac{E_1}{I_1} = \frac{1}{g_{11} - g_{12} g_{21}/(g_{22}+R_L)} \tag{7}$$

Output resistance

$$R_o = \left.\frac{E_2}{I_2}\right|_{e_s=0} = g_{22} - \frac{g_{12} g_{21}}{g_{11} + 1/R_s} \tag{8}$$

Efficiency

$$\eta = \frac{E_2}{E_s} = \frac{g_{21}}{(1 + R_s/R_i)(1 + g_{22}/R_L)} \tag{9}$$

Notice that by idealizing the terminations ($R_s = 0$ and $R_L = \infty$) Equations (7), (8), and (9) describe the intrinsic characteristics of the modulator. The problem of relating photocell parameters to photochopper performance is thus reduced to examining their effects on the g-parameters.

Since the cell parameters of lit resistance and recovery speed are affected by the light level, it is necessary to establish a standard illumination for the analysis. A convenient and adequate source of illumination is a neon lamp, which gives a typical illumination of 600 μwatts/cm^2. Due to recovery time effects, the waveform of the illumination may also be important. A definition of illumination waveform terminology is presented in Figure 3.

With an illumination waveform that provides a zero dark time, the conductivity of the two cells in series is maximum at the instant illumination is removed from one photocell and applied to the other; it decays toward the dark conductivity of the cell which was darkened at that instant.

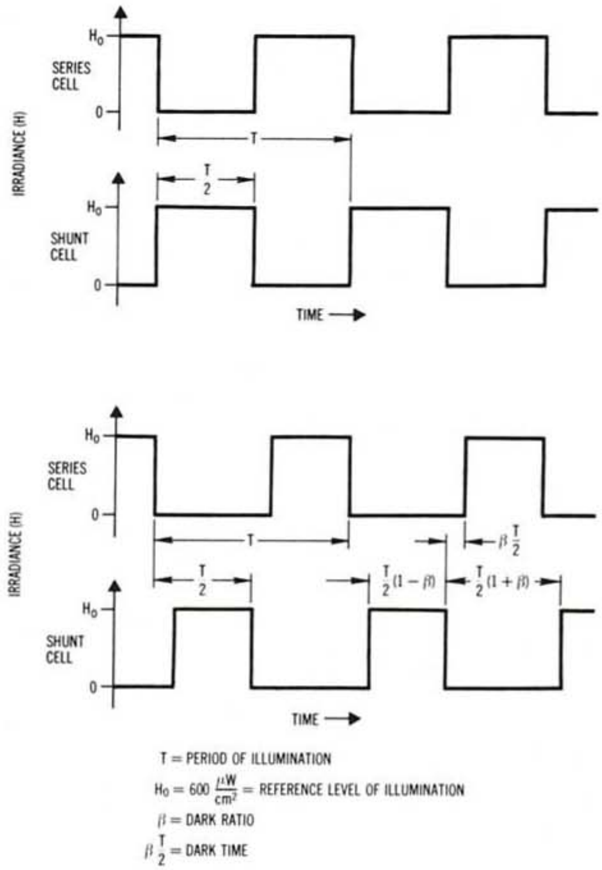


Figure 3. Illumination Waveforms

This transient proceeds until illumination is once again reversed. The resulting conductivity of the two cells in series as a function of time is a train of impulses, with amplitudes proportional to lit conductance, and tails proportional to recovery time of the cells. If the frequency of the illumination waveform is increased without bound, the conductivity function smooths out until each cell has an average resistance R^* corresponding to the average illumination $\overline{H}$ whose relationship to the standard illumination H_o is given by

$$\overline{H} = H_o \frac{1-\beta}{2} \tag{10}$$

By considering this pattern of illumination as applied in the circuit of Figure 2, it is clear that the g_{11} parameter exhibits precisely such a variation with frequency of illumination waveform, that is, it has a conductivity approaching zero at very low frequency, increasing with frequency and levelling off to a value of $1/2R^*$ at high frequency.

Similarly, g_{22} is the reciprocal of the average conductivity of the two photocells in parallel, and since at very high frequency each cell approaches R^*, the value of g_{22} approaches

$R^*/2$. As the frequency is reduced, however, g_{22} does not decrease without bound the way g_{11} does, but rather approaches and levels off at a value of resistance which is half the average resistance of one cell. This is approximately R_{lit}, because each cell is exposed to H_o approximately half the time.

It was previously stated that part of the design objective is to make input resistance of the photomodulator high and output resistance low. This means that the selection should aim at making both g_{11} and g_{22} as small as possible, since they comprise the major contribution to the value of input conductance and output resistance, respectively. Figure 4 indicates that these parameters are degraded at frequencies above a particular frequency. This cutoff frequency relates to photocell recovery time, and shifts up or down in the spectrum inversely as the recovery time.

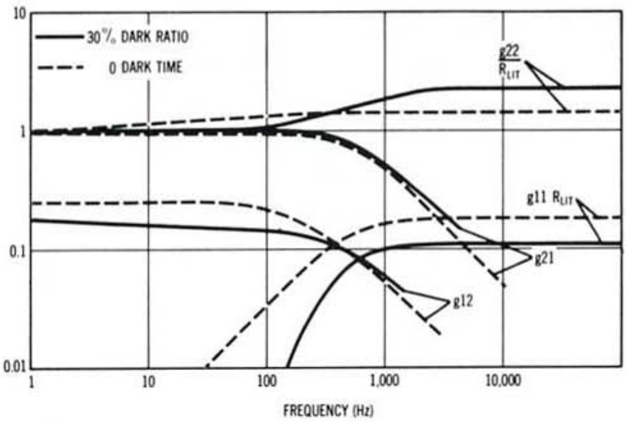


Figure 4. Normalized g-Parameter vs Chopping Frequency

Figure 4 also shows a plot of the forward transfer coefficient g_{21}, which is of major interest in photomodulator design. It is clear that g_{21} is also degraded by the higher frequencies of cyclic illumination. In fact, the only parameter which is not degraded by high frequency operation is the reverse transfer coefficient g_{12}. Obviously, photocell recovery speed can be very influential in establishing photomodulator performance. As a guide to the designer in selecting a photocell, the approximate relationship between the transfer coefficient (chopping efficiency) cutoff frequency is given by

$$f_{cell} = \frac{1}{2T_{10}} \qquad (11)$$

where T_{10} is the time required after removal of illumination for the photocell's conductance to decay to one-tenth of its value with illumination applied.

Figure 4 also illustrates the effect of introducing dark time to the cycle of illumination. Clearly, dark time has little effect on efficiency and output resistance, but it has a dramatic effect on input resistance, especially at frequencies low with respect to the cutoff frequency. By means of dark time it is thus possible to optimize with respect to the other parameters for best signal-to-noise ratio, then adjust the dark time to obtain an adequate input resistance.

SELECTING THE CHOPPING FREQUENCY

Three factors should be considered in selecting the chopping frequency:

1. Overall system bandwidth requirement.
2. Amplifier noise corner.
3. Chopper efficiency cutoff frequency.

A general requirement usually is to make the overall system bandwidth as great as possible, which implies operation of the chopper at the highest possible chopping frequency. In some cases this requirement may have sufficient weight to force a compromise with signal-to-noise ratio. However, as was stated at the outset, this discussion concerns only SNR optimization, and other considerations are mentioned only if they adversely affect SNR.

Since maximum SNR has primary importance as the design objective, the only consideration is the tradeoff between the chopper efficiency cutoff frequency and the amplifier noise corner. At very low chopping frequencies, the bandpass spectrum of the chopper amplifier includes enough of the flicker noise to make the SNR obtained much less than might be possible at higher chopping frequencies. As the chopping frequency increases, SNR improves, due to reduced noise, until it reaches the point at which the rate of decline of the noise is reduced (past noise corner); the frequency yielding maximum SNR occurs when the rate of decline of the noise is exactly balanced by the rate of decline of the chopping efficiency. Beyond this frequency, the SNR is only worse. There are three possibilities to consider: photocell cutoff frequency greater than, equal to, or less than amplifier noise corner f_N. Each of these possibilities is illustrated in Figure 5.

Obviously, it is desirable to always have the chopper efficiency cutoff frequency much greater than the amplifier noise corner, but this relationship is not always a matter of choice. The need for thermal stability and sensitivity in the photocell precludes the manufacturer's use of the higher-speed material (cadmium selenide). In addition, environmental problems may prevent construction of an amplifier with a sufficiently low noise corner to come in much below the chopper cutoff frequency.

The best chopping frequency is selected in either of two ways. If the amplifier noise corner is known, and the recovery speed of the photocells are known, Equation (11) is

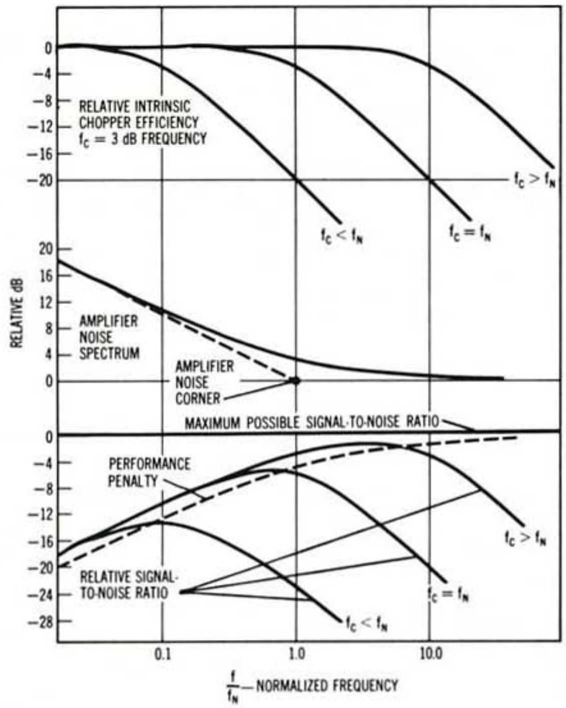


Figure 5. Signal Noise and SNR vs Normalized Frequency

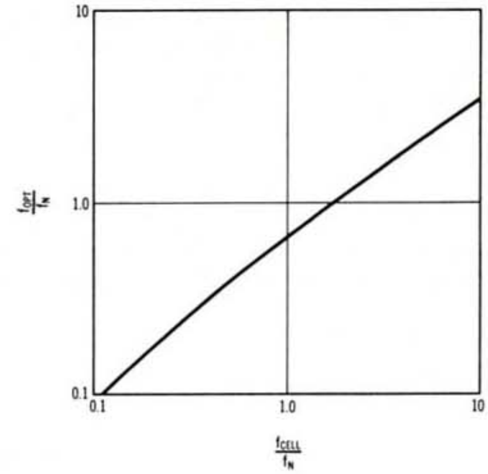


Figure 6. Optimum Chopping Frequency as a Function of Photocell Cutoff Frequency – Both Normalized to Amplifier Noise Corner

used along with Figure 6 to compute the optimum chopping frequency. The procedure is as follows:

1. Compute the ratio of the photocell cutoff frequency f_{cell} to the amplifier noise corner frequency f_N.

2. Use the value of f_{cell}/f_N to enter the curve in Figure 6 and obtain the value for the ratio f_{OPT}/f_N.

3. Compute the optimum chopping frequency by multiplying f_N by the value of the ratio taken from Figure 6.

4. Use the dotted line curve in the family of relative signal-to-noise ratio curves in Figure 5 to obtain the relative signal-to-noise ratio which would be obtained at the optimum frequency.

If the signal-to-noise ratio obtained under these conditions is not adequate, the only remedy is to select either a faster photocell or an amplifier whose noise corner is at a lower frequency.

As a numerical example, consider a photocell with T_{10} = 1.0 msec which is to be used with an amplifier whose noise corner is 100 Hz. From Equation (11) compute

$$f_{cell} = \frac{1}{2T_{10}} = 500 \text{ Hz} .$$

This gives a ratio f_{cell}/f_N of 5.0. Entering Figure 6 with this value on the abscissa gives a ratio f_{OPT}/f_N = 2.1. Applying this number to the noise corner gives the result:

$$f_{OPT} = f_N \times \left(\frac{f_{OPT}}{f_N} \text{ FROM CURVE}\right) = f_N \times 2.1 = 210 \text{ Hz} . \quad (12)$$

Entering the dotted line curve on Figure 5 with this ratio of 2.1 gives a value of about −2.5 dB. This means that the chopping frequency of 210 Hz places the operation within 2.5 dB of the best possible signal-to-noise ratio obtainable with this amplifier, no matter how fast the photocell is, or, conversely, the best obtainable with this photocell, no matter how far down the noise corner might be shifted. The dotted line may therefore be described as the penalty curve, since it evaluates the performance penalty for choosing a more stable, and hence slower, photocell. A detailed evaluation of the benefit of this selection is really not necessary when designers consider the problems of potential servo loop instability and excessive thermal noise which may result with photocells whose resistances have high temperature coefficients.

SELECTING THE METHOD OF ILLUMINATION

It was necessary to assume standard illumination (i.e., level specified by the manufacturer for stated performance of photocells) for the preceding discussion. However, the specified level is not always best in every given situation. The photocell parameter tradeoff is that at reduced irradiance the lit resistance is higher and the recovery time is longer, both of which may degrade performance, depending upon the design circumstances.

Suppose, for example, that the associated amplifier being considered has a very low noise corner, and a plot of noise versus source resistance for the amplifier shows that a higher noise figure could be obtained with a photocell modulator having a lit resistance that is higher than specified by the manufacturer. This would definitely indicate the advantage of using a lower level of illumination than that specified, since it would establish a higher input resistance and require less power to provide illumination (a serious consideration for portable or battery-operated equipment). The only drawback is that the lower level of illumination allows a higher temperature coefficient.

Conversely, if the associated amplifier has a high noise corner and is optimized for noise figure by a lower source resistance, performance would unquestionably be better with a higher level of illumination. But here, too, there is a drawback; at the higher irradiance the input resistance would be reduced, although operation would be more stable with temperature change.

In general, unless there is a compelling reason to deviate, use of the manufacturer's specified irradiance is recommended. This leaves only two choices to be made: the type of irradiance source and the method of modulating it.

Almost any kind of source can be used, except those monochromatic sources with spectral peaks far beyond the skirts of the photocell response curves. Examples of unsuitable sources are ultraviolet sources, such as mercury vapor lamps, and infrared sources, such as gallium arsenide diodes. Although they produce a photoconductive response, the match is poor. Only very peculiar circumstances would justify the use of any kind of laser, gaseous, solid, or injection type of source. The most common sources also happen to be the most suitable: neon or incandescent panel lamps. For incandescent lamps a mechanical method of modulating the irradiance is usually necessary, since the thermal time constants of typical filaments are much too long for most chopper applications. Although a number of units are available which package a photocell and an incandescent lamp together they are intended for applications beyond the scope of this discussion.

Neon panel lamps are at present the most practical source for photocell illumination in photochopper applications; they have a spectral radiant peak at the optimum wavelength, fast on-and-off capability, and a fair tolerance of vibration. One disadvantage of neon lamps is that ignition causes a large, fast voltage transient which occurs at the chopping frequency and is thus capable of producing an extraneous dc offset. An effective remedy is the electric shield mentioned earlier. The only other significant disadvantage is the high voltage requirement. This is especially aggravating when battery operation is being considered, but the difficulty is by no means insurmountable. Several techniques exist for cyclically driving neon lamps from a battery supply; it is not a serious problem and need not be discussed here.

Another possible source which should be mentioned, in view of the recent improvements in its performance, is the solid-state spontaneous emitter. Specifically, the family of gallium arsenide phosphide sources has a suitable wavelength, but its radiation level is at present a little too low for consideration in a practical photochopper. It is close, though, and when efficiency improvements make the necessary radiation level practical, they will offer the advantage of a low-voltage source of illumination, ameliorating part of the illumination problem.

At the present state of illumination technology, neon lamps of the high-brightness type are recommended for illuminating photocells in photochopper applications. The only exception is the need for incandescent illumination when the synchronous lamp voltage is intolerable, necessitating mechanical modulation.

SELECTING THE ILLUMINATION WAVEFORM

Mentioned previously was the effect of providing a portion in the illumination cycle during which both the shunt and series photocell illuminations are zero. The curves shown in Figure 4 give the effect of only one value of this dark ratio. Nevertheless, the trend is clear. Introducing a dark ratio is always beneficial, and its use is recommended whenever it is practical. The only circumstances making it impractical occur when, for reasons of component or space economy, it is necessary to use a very simple neon drive circuit, such as a neon relaxation oscillator. The question, therefore, is not whether or not to use dark time in the illumination waveform, but how much dark time to use.

Although both terms "dark ratio" and "dark time" have been defined, the former is related to the photocell speed parameter only via the chopping frequency, as shown in Figure 6, whereas the latter is related directly. Both terms were defined, however, because in some illumination drive circuits the dark ratio remains constant as chopping frequency is adjusted, while in others the dark time remains fixed. Regardless of which definition is used, the basic guide to adjustment of the dark time is to make it approximately equal to T_{10}. This can be expressed analytically as

$$\frac{\beta T}{2} \approx T_{10} \qquad (13)$$

This selection rule should really be regarded as a definition of the upper limit on (rather than an optimum adjustment of) dark time, for two reasons:

First, the incremental benefits of dark time decrease with increasing dark time, so that little is gained for dark time greater than T_{10}.

Secondly, it is clear that dark time cannot exceed T/2!

SELECTING THE AMPLIFIER

Needless to say, with maximum SNR as the objective, the amplifier selected should be a low-noise type. More importantly, the amplifier's noise corner should be as low as possible. If the input resistance of the photochopper is high, the output resistance (via lit resistance) is also high, though considerably lower than the input resistance. If this high output resistance is to be the optimum source resistance for the amplifier, the amplifier must have a high ratio of short-circuit noise voltage to open-circuit noise current (as discussed earlier). This condition is usually, though not necessarily, accompanied by a high input resistance for the amplifier. Amplifier selection thus tends in the direction of high input resistance.

Another benefit of a high input resistance amplifier is the improved modulation efficiency, as indicated in Equation (9), in which R_L – the load on the output of the photomodulator – represents the input resistance of the amplifier.

Bandwidth is not much of a problem, since most of the signal power will be contained in the fundamental, second, and third harmonics of the chopping frequency. Such bandwidths are easily realizable with ordinary transistor amplifier techniques. It is advisable, however, to avoid shaving the bandwidth too closely, because the phase shift which accompanies the high-frequency roll-off could impair the demodulation efficiency, and hence the overall dc-to-dc gain. The customary practice is to limit the bandwidth only enough to prevent noise from preceding stages saturating the output stage. This permits the use of a demodulator output filter whose time constant can be more freely adjusted to meet the overall system bandwidth requirement and still provide the desirable single-pole roll-off. This range of adjustment simplifies the closed-loop stability problem.

Figure 7 shows the schematic diagram of a possible amplifier. This amplifier produced the noise-vs-source resistance curve in Figure 1, and the noise-vs-frequency curve of Figure 8. With an input resistance considerably more than one megohm, it is well suited for use with a photomodulator whose output resistance matches the optimum value of 16 k,

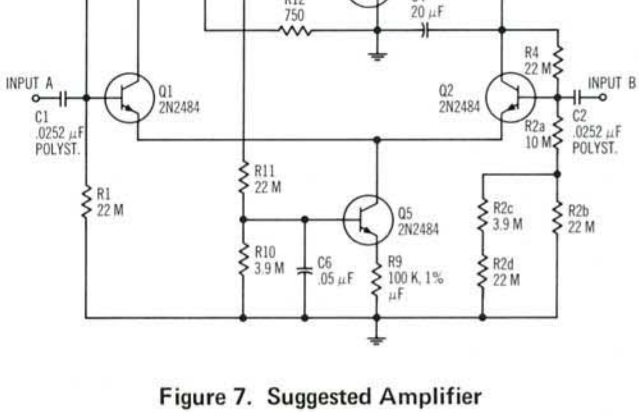


Figure 7. Suggested Amplifier

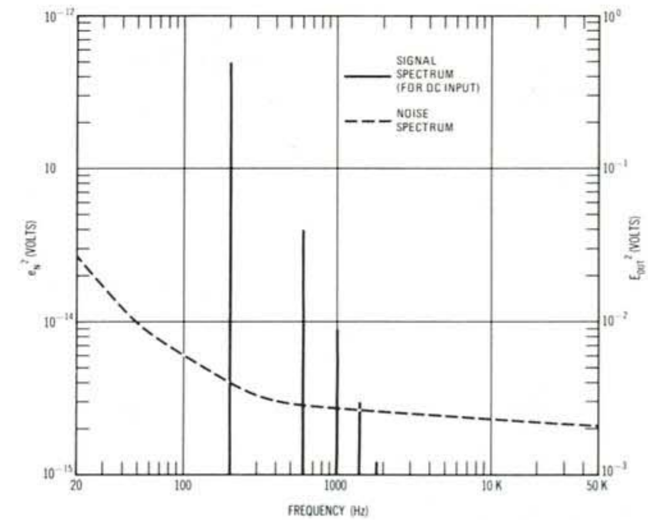


Figure 8. Spectra of Signal and Noise

as determined in Figure 1. With a noise corner of approximately 100 Hz (Figure 8), this amplifier could also be employed as the example leading to the results of Equation (12); hence a chopping frequency of about 200 Hz would be appropriate. Figure 8 presents a dramatic illustration of the precise manner in which chopping improves the signal-to-noise ratio. The square of the equivalent noise voltage at the input is plotted on the log frequency abscissa; also plotted for comparison is the square of the spectral components resulting from an input of ONE MICROVOLT DC! Clearly with an adequate restriction of the bandwidth (by filtering the demodulator output) practical values of SNR can be obtained with small fractions of a microvolt.

CHOOSING ELECTRICAL ARRANGEMENT

As shown in Figure 9, six possible choices exist for a modulator configuration. Each of these has been illustrated with an arrow in the photocell to indicate the phase position of illumination, and each of the six has been drawn to have the same input-output phase relationship. What, then, are the differences?

There are two basic groups: half-wave and full-wave. Within each group are a number of possible configurations, of which the three most basic are illustrated. Other combinations, using transformers, are omitted for lack of relevance. For a particular combination – single-series, single-shunt, or series-shunt – the full-wave circuit has the advantage over half-wave with respect to SNR, although the input resistance of the full-wave combination will always be exactly half that of the half-wave combination. Since maximum SNR is the objective in this discussion, the full-wave combination will ordinarily be preferred, the only exception being made for those cases in which extremely high signal source resistances are anticipated.

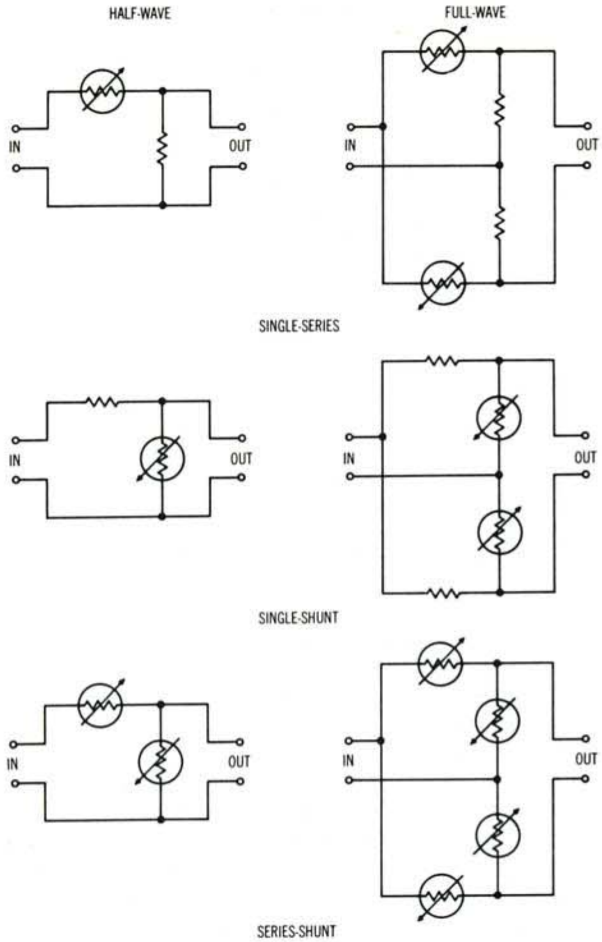


Figure 9. Modulator Electrical Arrangement

CHOPPER AMPLIFIER ELECTRO-MECHANICAL LAYOUT

Design selections for electro-mechanical layout are perhaps the most subjective in the entire system. There are, however, three areas in which the design selections should be made objectively. They concern mainly the layout of the input, consisting of the input terminals of the amplifier and the photomodulator. The three basic categories are: electrical connections, electrical insulation, and thermal arrangement.

Connections

Although the use of short-as-possible pigtails is a fairly standard practice, the exercise of this practice is especially important in circuits involving very low level dc voltages. Photocells have lead materials whose thermocouple voltages may be quite high with respect to copper, and the closer together the connections are, the less likely it is that a thermal gradient will appear across cell connections. Keeping the connections close together usually requires making the leads short. But there is another reason for shortness. Pickup of ac signals at the input must be avoided. Although the system is a dc amplifier, the presence of high level ac signals can cause a reduction of gain by saturating the higher-level stages of the amplifier. What is worse, however, is that if the stray ac signals have a component at the synchronous (chopping) frequency, this component will subsequently be synchronously demodulated, resulting in extraneous dc outputs or offsets. Unless there are cogent and compelling reasons to do otherwise, the leads must be kept short to prevent stray ac pickup and to simplify the reduction of thermocouple voltages.

Insulation

Selection of materials for insulating the connections at the input is also critical because some materials are capable of producing extraneous dc signals. This comes about as the result of polarization of dielectric materials in certain types of capacitors, and from chemielectric effects in materials which are capable of absorbing moisture. Polarization (or "soak") can be avoided by using capacitors whose dielectric is polystyrene or some other material of similar qualities. These capacitors should be used in any circuit position at the input where a direct-current path exists from either side of a capacitor to the ungrounded "hot" side of the input. Chemielectric effects usually occur when impurities within a material, or deposited upon its surface, are electrolyzed by the presence of moisture which is either absorbed by or deposited on the surface of the material. Porous materials, such as bakelite, phenolic, and nylon, should therefore be avoided. Teflon, polystyrene, and ceramic are the preferred insulating materials. Glass is good, but in the form of fibreglass it can be troublesome in the presence of high humidity. Some good plastics are polypropylene and dialylphthalate.

Thermal Arrangements

Thermal arrangements are difficult to define, and more difficult to characterize. The objective in designing the thermal arrangement is to minimize thermal gradients among connections to the photocells and through the entire photochopper region. This is done by mounting the photocells and the source(s) of illumination within a monolithic block of material having good heat conduction properties, then surrounding the block with insulating material. If there are nearby sources of heat, it may be necessary to place this in an insulated chamber with heat-conducting walls, but a simpler practice usually is to locate the chopper assembly away from local sources of heat. The monolithic block in which the photocells are mounted can, of course, be custom made by the designer, but Hewlett-Packard mass produces at low cost a chopper assembly which is capable of mounting both modulator and demodulator cells in a good electrical configuration, since the leads emerge from opposite sides of the monolithic block and can thus be electrically isolated with ease. The block material has good heat conduction; the block design permits both small size and the heavy walls necessary to establish an effective thermal shunt around the photocells. For these reasons, the HP5082-4511/12/13/14 chopper assembly is highly recommended for any and all photochopper applications. With a proper amplifier and neon drive circuit it is optimized with respect to all the criteria raised in this discussion.

CONCLUSION

While much has been written about chopper amplifier design, and much more could be written here, the areas covered in this note have in the past been approached mainly by guesswork. The material presented focused on optimizing signal-to-noise ratio through carefully conceived design criteria for selecting chopper components. Included in this discussion were techniques for optimizing operating conditions and guidelines for circuit design and layout. With this information, optimizing SNR in chopper amplifiers can now be performed with confidence.