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SEMICONDUCTOR PHOTODETECTORS AND ELECTRICAL NOISE IN OPTICAL PHOTODENSITOMETRIC EQUIPMENT FOR QUANTITATIVE ASSESSMENT OF THIN MEDIA CHROMATOGRAMS

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SUMMARY

This paper considers the electrical noise originating in photodetector devices and associated amplifier equipment of photodensitometric instruments intended for quantitative assessment of thin media chromatograms. From a comparison of optical and electrical noise values the minimum intensity of illuminating light is calculated, which is necessary to meet a prescribed performance standard. Photomultiplier tubes and solid-state PIN-diodes are compared and it is shown that it is feasible to use these devices for high grade photodensitometric work. Advantages accrue both in the electrical and mechanical design of the instrument, and there is a resultant decrease in the expected costs plus an easier mode of operation.

INTRODUCTION

In two recent papers[1,2] the authors discussed optical background noise and its implications for the ultimate sensitivity and accuracy of photodensitometric methods for the quantitative assessment of thin media chromatograms. Measures designed to decrease the amount of optical noise present in various densitometric arrangements were described and analysed. If, however, the optical noise is reduced to very low levels, another source of noise becomes important, and this may then limit the performance of the system. This other noise source is generated in the photoelectrical conversion unit and the subsequent electronic circuitry. It is an analysis of this aspect of noise to which this paper is devoted.

THE SOURCES OF ELECTRICAL NOISE

The most important source of electrical noise is actually the photodetector itself. Physically this noise is caused by random fluctuations in the number and energy of the charge carriers liberated by the incident light energy. The detailed mode of generation of the noise signal, however, varies considerably from one type of photodetector to another. It is not the purpose of this paper to consider these questions in detail; it will be left to the interested reader to look for specific information in the specialized literature.

The amplitude of the noise signal generated by a photodetector device is one of its most important characteristic parameters. Together with the radiant conversion sensitivity it determines the detection threshold obtainable, provided that—and this is usually the case—the noise of the subsequent amplifiers can be made equal to or smaller than the noise originating in the photodetector itself. From elementary considerations it can be shown that only the amplifier stages immediately following the detector need to be considered; the remainder of the circuit can usually be neglected in this context.

From an electrical point of view, the photodetector can be represented by an ideal signal generator i_s, a noise generator i_ν, an internal impedance Z_i, and a load impedance Z_L (Fig. 1). The photodetector devices most suited for the present application can electrically be considered as current generators. It is, therefore, convenient to draw the equivalent diagram in Fig. 1 on this basis. The current generators shown are assumed to have infinite impedance. The internal dynamic impedance of the detector is represented by Z_i, connected in shunt to the terminals of the equivalent generators.

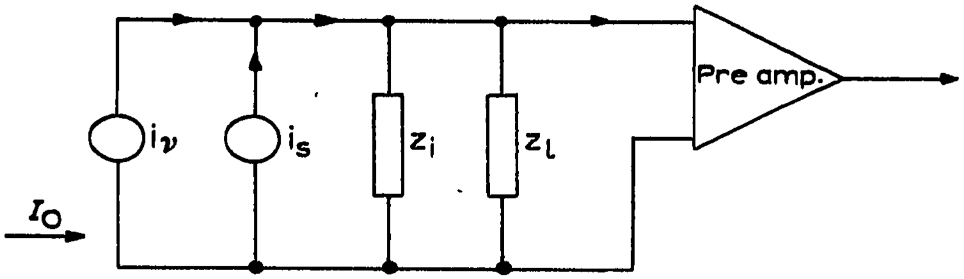

Fig. 1. Equivalent circuit of photoelectric convertor. i_ν = noise current generator; i_S = signal current generator (both ideal with infinite impedance); I_0 = incident light intensity; Z_i = internal impedance; Z_L = load impedance.

Since we are concerned here with slowly varying signals containing only very low frequency components, Z_i can be considered as a pure resistance R_i and the same also holds usually for the load impedance, Z_L, which includes, of course, the amplifier input impedance. For the best energy transfer from the photodetector to the amplifier chain, R_i should be equal to R_L. For current generating devices with high values of R_i, this rule may prove impractical. In these cases, R_L should be as large as is consistent with noise and supply voltage requirements.

There is a noise voltage across the terminals of any resistor, the r.m.s. value of which is determined by the relation:

$$e_{\nu_R} = 0.126\sqrt{R \cdot \Delta F} \cdot \mu\text{V} \tag{1}$$

or in terms of noise current

$$i_{\nu_R} = 0.126\,\frac{\sqrt{\Delta F}}{R} \cdot 10^{-3}\,\mu\text{A} \tag{1a}$$

In this equation R is the resistance value in kΩ, and ΔF the bandwidth of the system in kHz; the resistor is supposed to be at room temperature. The value of e_{rR} is the minimum value, compatible with a given resistance at room temperature. If this resistance is connected across the input terminal of an amplifying element, the noise measured at the output is always larger than the value which can be calculated from eqn. 1. The reason is that any amplifying element generates some noise of its own. This increase in noise as compared with that due to the input resistance is expressed by the noise figure of the amplifier, *e.g.*, a noise figure of 3 dB means that the total noise power at the output could be thought of as being produced by an ideal noise free amplifier with two times the noise power of the input resistor, that is $\sqrt{2}$ times e_{rR}, at the input. The noise figure of a given amplifier is a function of the input resistance R_1; for a certain value of R_1 it shows a usually rather flat minimum, to both sides of which it increases. Typical values for a well-designed amplifier at moderate values of R_1 up to a few MΩ are 3 dB, though rather lower values may be achieved. At very high values of R_1 (order of tens of MΩ are required for some types of photodetectors) usually higher noise figures have to be considered.

From the electrical point of view it is convenient to express the noise produced by the photodetector itself in terms of a noise figure, related to the circuit resistance (R_t in parallel with R_L), chosen for optimum conditions.

This figure states how many times the noise current (or voltage) generated by the photodetector exceeds the thermal noise of the total circuit resistance.

If this noise figure is larger than the noise figure of the associated amplifier, only the noise contribution from the photodetector has to be considered. This is the case with photomultiplier tubes with their high built-in current amplification; with solid-state photodevices an individual examination is necessary.

THE OPTICAL NOISE EQUIVALENT POWER

The intrinsic noise of the photodetector itself is the limiting threshold for the lowest light intensity which may still be detected with some degree of reliability. For these and related considerations on the optical side of the device, it is, however, preferable to express the noise output in optical units. To this purpose, the optical noise equivalent power (NEP) is introduced; it defines an optical input intensity (in W or lumens) that produces an output signal of the detector which is equal to the r.m.s. value of the detector noise signal at a bandwidth of 1 Hz.

The noise equivalent power of different types of photodetectors may differ by several orders of magnitude. With high grade photomultiplier tubes values down to about 10^{-16} W may be obtained. (Much lower values are available in special purpose tubes; for general application, however, the cost of these devices is almost prohibitive.) With solid-state devices the lower limit lies at present at NEP values of the order of 10^{-11} to 10^{-14} W. The minimum detectable light intensity of phoultomtiplier tubes is, therefore, several orders of magnitude lower than that of solid state devices.

PHOTOMULTIPLIERS *versus* SOLID-STATE DEVICES

Up until now photodensitometric devices have always employed photomultiplier tubes. Despite their high sensitivity and excellent noise performance, photomultiplier tubes have several drawbacks when compared with solid-state devices. These disadvantages make the use of the latter attractive.

High sensitivity photomultiplier tubes are rather expensive. In addition, they need sophisticated and, therefore, expensive accessories. Their high-voltage supply has to be precisely regulated and divided among the dynodes. The tube has to be protected against optical overloading, which may lead to irreversible changes in the characteristics and even to self destruction.

Among the different types of solid-state photodetectors it appears that the PIN-diode (p-intrinsic-n) is best suited to the requirements of the present problem[3]. At present there are under development solid-state photodevices with built-in (avalanche) current multiplication. These devices will, when (commercially) available, reduce the advantages of the conventional photomultiplier still further. As compared with photomultiplier tubes we find on the credit side that these diodes are much smaller and more rugged; mounting problems are, therefore, considerably eased. The voltage requirements are modest, being of the order of 20 V, and adequate stabilization does not present a problem. The spectral sensitivity characteristic is much flatter than that of most photomultipliers and their long term stability is much improved. Magnetic interference is of no concern and optical overloading is easily tolerated. On the debit side their slower response is of little consequence for the purposes envisaged in the present requirements. Their low output signal at high impedance levels requires, however, careful design of the associated amplifier equipment in order to keep the noise figure low. High input impedance–low noise junction field effect transistors appear to be the best solution for this purpose.

Both photomultiplier tubes and PIN-diodes are essentially current-devices with very high internal impedance. Their noise contribution at a given bandwidth ΔF is, therefore, basically determined by the dark current i_D according to the relation:

$$i_v^2 \simeq 1.6\, i_D \cdot \Delta F \cdot 10^{-10}\, \mu\mathrm{A} \qquad (\Delta F[\mathrm{kHz}],\, i[\mu\mathrm{A}]) \tag{2}$$

The luminous sensitivity β of a photomultiplier tube or any other high impedance photoelectric device is defined as the change in output current per lumen (or W) of incident radiant flux. Using this conversion factor we obtain the noise equivalent light power N_0:

$$N_0 \simeq \frac{i_v^2}{\beta \Delta F} = \frac{1.6\, i_D}{\beta} \cdot 10^{-13}\,\mathrm{W} \qquad (\beta[\mu\mathrm{A/W}]) \tag{3}$$

Eqn. 2 holds under the assumption that the noise originating in the photodevice is essentially white. White noise is caused by completely random fluctuations—in this case the instantaneous number of charge carriers (electrons, holes)—around an average value. Characteristic for white noise is a spectral power density, which is constant throughout the relevant range of frequencies as is the case with white light. In the "white" region the total noise power is therefore proportional to the bandwidth of the signals.

In most electronic elements, however, the power density of the noise increases sharply at very low frequencies. Below a certain crossover frequency the spectral power density instead of being constant rises with $1/f$ (f = frequency). This results in a considerable increase in noise in the very low frequency region (above the value calculated from eqn. 2).

THE OVERALL NOISE EQUIVALENT LIGHT INTENSITY

The above-mentioned dependency of the noise at very low frequencies (called the "flicker noise region") leads to a considerable increase in noise for signals with very low frequencies. Typically the crossover frequency between the $1/f$ portion and the "white" part of the spectrum is of the order of a few hundred Hz. For this reason, it is advisable to transpose very low frequency signals to a higher position along the frequency axis. In optical information retrieval systems this is most easily accomplished by chopping the light beam at a rate which is well above the crossover frequency. The chopping frequency acts as a carrier, modulated by the original signal. In this way, the original signal is shifted to a higher frequency region of the spectrum, where the noise of the photodetector and associated amplifier equipment is lower. Chopping the light beam, therefore, not only bypasses the problems associated with d.c. amplification, but also improves the signal-to-noise ratio, provided the chopping frequency is sufficiently high. A drawback of chopping the input light beam is that it actually reduces the incident light signal and, therefore, the output signal level of the photodetector by 1/2. It can be shown that by using special (so called "synchronous") detection techniques following the pre-amplifier stage, half of the noise energy can be suppressed. The result is equivalent to a $\sqrt{1/2}$ decrease of the light loss caused by chopping. Alternating the light beam between two detectors working into a common differential input amplifier instead of straight interrupting of the beam offers a similar improvement. In general, however, the gain of these more sophisticated procedures does not warrant the expense; (see also ref. 2).

The chopping frequency has to be removed at a point of suitably high signal level by demodulation and smoothing the signal, so that a replica of the original light signal is restored. The required bandwidth of the chopped signal for a fixed slit scanning device is

$$\Delta F > \frac{V}{W} \tag{4}$$

Here V is the transport velocity of the paper perpendicular to the slit and W the width of the slit. For a flying spot-scanning device this becomes (for a square-shaped or circular spot with no overlap)

$$\Delta F > \frac{V}{W} \cdot \frac{B}{W} = \frac{VB}{W^2} \tag{5}$$

where B is the width of the scan. The term V/W represents the number of scanning lines per second and B/W the number of independent points per line.

After amplification the chopped signal has to be demodulated (rectified). To remove the chopping frequency, the demodulated signal is filtered and smoothed. The bandwidth of the signal after this operation is approximately $\Delta F/2$. Frequently, however, further filtering and integrating is advisable, resulting in an effective output bandwidth $\Delta F_0 \ll \Delta F/2$. The result is a decrease in noise by a factor $\sqrt{2\Delta F_0/\Delta F}$. The reason for this is that it is the final bandwidth which counts and it is of no importance when the bandwidth limitation (filtering) is performed.

With N_0 being the noise equivalent power of the photodetector, we obtain an equivalent input light intensity

$$I_{\nu_E} = N_0 \sqrt{\Delta F} \tag{6}$$

If two independent photodetectors are used as for example in the double beam device now being designed in our laboratories, the electrical noise power is increased by a factor of 2 and the noise amplitude by $\sqrt{2}$. This is because the noise contributions of both photodetectors are independent and non-correlated. This is true regardless of whether difference or ratio forming of the two signals is employed. In eqn. 6, therefore, a factor of 2 has to be added under the square root sign.

If the preamplifier noise contribution cannot be neglected, it has to be included in expression (6). Let us assume that the preamplifier increases the total noise power by a factor of K as compared to the photodetector alone. Then the factor K also needs to be inserted under the square root sign in eqn. 6.

$$I_{\nu_E} = N_0 \sqrt{2\Delta FK} \tag{7}$$

OPTICAL AND ELECTRICAL NOISE

In two recent papers[1,2] we have discussed steps which help to reduce the optical noise of chromatogram scanning devices. In order, however, to make full use of the low optical noise values now obtainable, the total noise equivalent light intensity (for the electrical noise) has to be equal to or smaller than the optical noise amplitude.

$$I_{\nu_E} \leqslant I_{\nu_{\mathrm{opt}}} \tag{8}$$

The optical noise differs from the electrical noise in that it is essentially multiplicative; it may, therefore, be expressed as a constant fraction of the light intensity I_0 at the photodetector input.

$$I_{\nu_{\mathrm{opt}}} = \bar{\bar{\nu}}_{\mathrm{opt}} \cdot I_0 \tag{9}$$

Similarly, the useful signal S_u is determined by the product of I_0 and the absorbance α_c of the investigated zone.

$$S_u = c \cdot \alpha_c \cdot I_0 \tag{10}$$

The lowest value of α_c, which may be determined with a given accuracy and reliability, is given by the ratio σ of useful signal-to-noise. Considering for the moment only the optical noise, we have

$$\alpha_c \geqslant \frac{\sigma \cdot \bar{\bar{\nu}}_{\mathrm{opt}}}{c} \tag{11}$$

This relation is valid if condition (8) is achieved. Assuming now, as a limiting case, that the equality sign in eqn. 8 is valid, we can write for the overall noise signal:

$$I_{\nu_{\mathrm{tot}}} = \sqrt{2} \cdot I_{\nu_E} \tag{12}$$

Using eqns. 7 and 11, I_0 can now be expressed as a function of the minimum value of α_c to be detected. As before, we have to postulate a minimum signal-to-noise ratio σ. Here we have, however, to take into account the fact that the electrical output signal is reduced due to chopping. Assuming simple chopping and subsequent rectification, the reduction factor is as previously described 1/2. Taking account of these considerations, we find for an arrangement using two separate photodetectors:

$$a_c \geqslant \frac{\sigma\cdot 4N_0\sqrt{\Delta F}\cdot K}{I_0\cdot c} \approx \frac{4\sigma N_0\sqrt{\Delta F}\cdot K}{I_0} \qquad (c \approx 1) \tag{13}$$

Relation (13) permits the determination of the light intensity I_0 at the photodetector input, which has to be maintained for a given sensitivity and accuracy. The latter is mainly determined by the value of σ. In crude approximation, the accuracy in % is equal to $100/\sigma$. Since according to eqn. 4 ΔF is proportional to the scanning speed, one possibility of improving the resolving power of the instrument is to reduce the speed across the scanning beam.

A NUMERICAL EXAMPLE

The best way to illustrate the results obtained so far is probably to calculate a numerical example. Let us consider transmission measurements on Whatman No. 3 paper, with optical density 3.4. The corresponding transmittance is $10^{-3.4} \simeq 3\cdot 10^{-4}$. A high grade PIN-diode is supposed to be used as photodetector. Its NEP value N_0 is 10^{-13} W; the noise figure K of the amplifier is assumed to be 2 dB $\simeq$ 1.6, and the bandwidth of the chopped signal $\Delta F \simeq 160$ Hz. This latter value is based upon 4 lines per sec scanning speed and 40 points per line. Narrow-band filtering and integration of the demodulated signal is in this example disregarded. If this can also be applied it results in further improvements in the signal-to-noise ratio and the obtainable resolving power. The load resistor of the photodiode has to be reasonably large (of the order of $10^7\ \Omega$), if the value of K mentioned is to be obtained.

A high performance double beam scanning device is assumed with an optical noise value $\bar{\nu}$ below 10^{-3}; the required accuracy for the weakest signal is to be of the order of 10%, corresponding to a signal-to-noise ratio $\sigma \geqslant 10$. The weakest change in absorbance which may be detected with this accuracy is, therefore, about $c_{\min} \approx 10^{-2}$ natural units or about $4\cdot 10^{-3}$ in optical density (decimal) units.

Introducing these parameters into eqn. 13, we obtain for the light intensity required at the photodetector input:

$$I_0 \geqslant \frac{4\cdot 10\cdot 10^{-13}\cdot 16}{10^{-2}} = 6.4\cdot 10^{-9} \tag{14}$$

The principle sources of attenuation of the light beam are the optical density of the paper and the spectral band pass filter required to limit the energy of the beam to the absorption band of the substance investigated. Let us assume that the scanning beam is permitted to cover a spectral band about 3 nm wide[2]. The fraction of the total visible light energy radiated by the source, which falls into this band, depends upon the type of source used and upon the spectral position (colour) of the absorption band. Together with the losses in the filtering device used (interference filter, wide band monochromator), about 0.1% may be considered as a typical value. These two factors together result, therefore, in an attenuation of approximately $3\cdot 10^{-4} \times 1\cdot 10^{-3} = 3\cdot 10^{-7}$.

Further, we have to consider the losses in the remainder of the optical system and the fact that only a small spatial part of the total light flux of the lamp can be really utilized. Altogether, the useful radiant flux may be estimated to about 5% of the total light output.

With these estimates, we obtain a required optical output of the lamp in the visible region of the spectrum equal to:

$$I_{\text{tot}} \approx 6.4 \cdot 10^{-9} \cdot \frac{1}{3 \cdot 10^{-7} \cdot 5 \cdot 10^{-2}} \approx 0.43 \text{ W} \qquad (15)$$

This value may, of course, easily be obtained even with a certain power reserve, using a light source in the range of 100 to 300 W input power. It, therefore, appears that the use of semiconductor photodetectors in this field, which up to now has been an exclusive domain of photomultiplier tubes, is feasible and promising even for photometric equipment with very high performance standards. Careful design of the optical system with a view to efficient utilisation of the light flux of the lamp is, of course, a prerequisite. Integration over the whole zone area and smoothing, as considered in refs. 1 and 2, reduce the effective bandwidth ΔF of the system and should, therefore, bring about a further improvement of the obtainable sensitivity by a factor of 5 or more.

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