SIMPLE PHOTOMETER CIRCUITS USING MODULAR ELECTRONIC COMPONENTS

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INTRODUCTION

During the last several years we have seen a tremendous increase in the variety and performance of solid-state electronics. Many modular components have become available at attractive prices, which give the photobiologist workable alternatives to commercial light measurement instrumentation. More importantly, the availability and flexibility of these modules allows us to inexpensively construct specialized measurement devices.

The basic components of light measurements are a detector, a high voltage power supply (if the detector is a photomultiplier), an amplifier, and a read-out system. The detector can be a photodiode, phototransistor, photocell, pyrometer, or photomultiplier tube. For low light level measurements the photomultiplier is the detector of choice, but it requires a high voltage supply. No longer must the high voltage supply be a large piece of equipment; in fact a small potted module can now serve this function for most photomultipliers, and the power requirement of the module itself is low voltage d.c. The amplifier can also be a small modular component, as can the read-out system. In fact, the variety of amplifiers, digital meters, and counters as well as other more specialized modules (for example, frequency converters, multiplier-divider modules, log modules) allows us to custom design instruments for many specialized applications. This paper describes an instrument for general bioluminescence assay use with special capabilities for an assay requiring the measurement of the ratio of two light signals. The individual circuits, as well as the considerations of overall design and construction, are discussed.

OPERATIONAL AMPLIFIERS

The key component in design of the current amplifier for a photomultiplier, and in many circuits which are useful for read-out applications, is the operational amplifier (op-amp) (Graeme et al., 1971; Philbrick/Nexus Research, 1969; Vassos and Ewing, 1972). Op-amps are differential linear d.c. amplifiers with very high gain which can be utilized to implement a wide variety of analog signal processing functions. There are many types of modular amplifiers now available: for high input impedance applications, FET input amplifiers, and for low drift application, chopper stabilized op-amps. In addition, for special requirements for high current or voltage capabilities or high frequency response selected units are available. Figure 1 illustrates how some simple arrangements of components connecting the two inputs and the output of an op-amp can perform useful functions.

Referring to figure 1A, all of these circuits consist of a single-ended input and feedback from the amplifier output to one of its inputs. The overall performance of the circuit is dictated by this feedback and not the nature of the amplifier module itself. The simplest circuit shown (figure 1B) is the so-called voltage follower amplifier; in this application a voltage input signal is simply buffered by the amp. Many op-amps have high input impedance (particularly FET input op-amps), thus they can be used to buffer the output of a voltage source with a low current capability and drive a read-out device which requires a relatively high current. In circuit configurations of the type of figures 1C and 1D, the inverting input of the amplifier is used. This input is held by the amplifier at essentially ground potential by feedback; that is, the sum of currents flowing into the inverting input is zero. The current from the signal source is equalled by the flow of current from the output through the feedback components. The inverting input is often called the summing junction because the amp acts to sum the currents at this point to zero when appropriate feedback is applied. In the circuit of figure 1C, an output voltage is produced which is proportional to the input current; the proportionality constant is simply the feedback resistance times minus one (since the feedback current must be of equal magnitude but opposite in sign to the signal current). When a signal is from a voltage source rather than a current source, it is a simple matter to convert the voltage to a current for input. This is accomplished by connecting the voltage source to the summing junction through a resistor as in figure 1D. The ratio of the output voltage to that of the signal source voltage is now proportional to the ratio of the two resistors as shown. In each of these circuits a capacitor has been introduced across the feedback resistor to limit the frequence response. The time constant in seconds, which describes the response of the complete circuit, is simply the product of R_1 and C. A useful amplifier for the output of a photomultiplier employs aspects of both 1C and 1D (figure 2). Here the negative current from a photomultiplier anode is transduced by the op-amp into a voltage. With R_1 equal to 10 MΩ (10^7 ohm), -10^{-8} amps would give a 0.1-V output signal. In order to cancel any dark current from the photomultiplier, a positive voltage can be selected using R_3 to feed a positive offsetting current into the summing junction through R_2.

PEAK HOLDING AMPLIFIER

A very useful circuit for bioluminescence assays is a peak holding circuit (Graeme et al., 1971; Philbrick/Nexus Research, 1969) (figure 3). Since initial

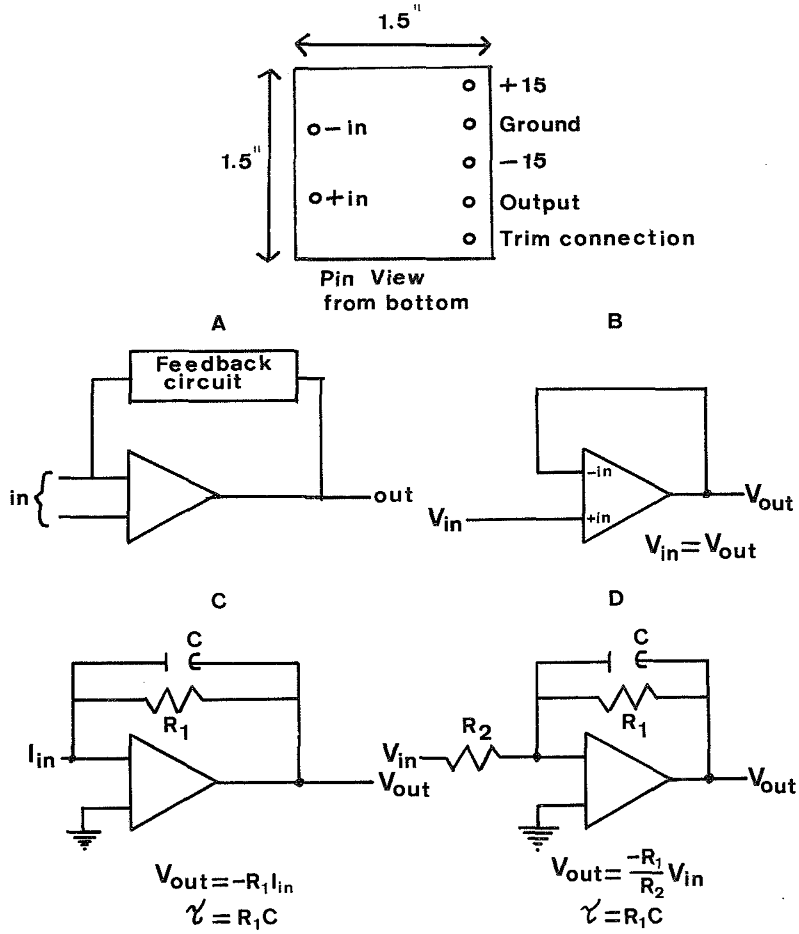

Figure 1. Operational amplifier circuits. A typical potted op-amp contained in a small module would have seven connecting pins as shown. Some simple circuits are (A) a general circuit, (B) a voltage follower, (C) a current-to-voltage transducer, and (D) an inverting voltage amplifier.

rate in many assays can be equated to the height of the flash peak, the peak hold allows the experimenter to read the peak value at his leisure. This simple circuit employs two op-amps in a noninverting configuration. The rate of change of the output after the peak is passed is determined by how leaky capacitor C_1 is and by the input impedance of A2. For this reason an FET op-amp is used for A2. Other peak hold circuits are discussed in the references given.

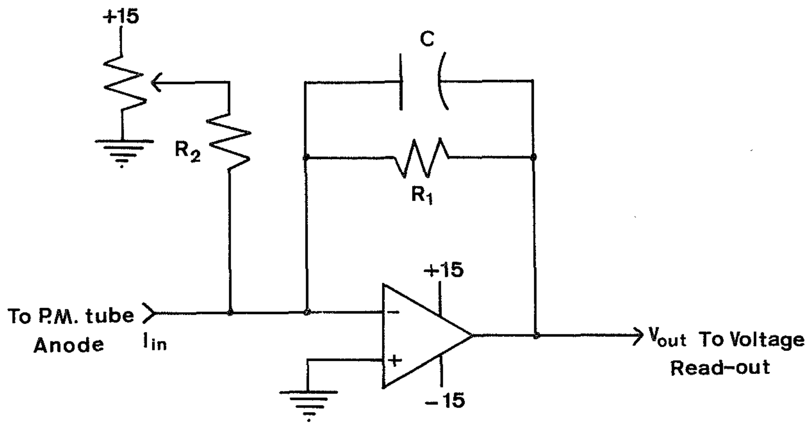

Figure 2. Practical voltage-to-current transducer for photomultiplier. An offsetting current for the photomultiplier dark current is selected via the potentiometer and supplied to the summing junction through R_2.

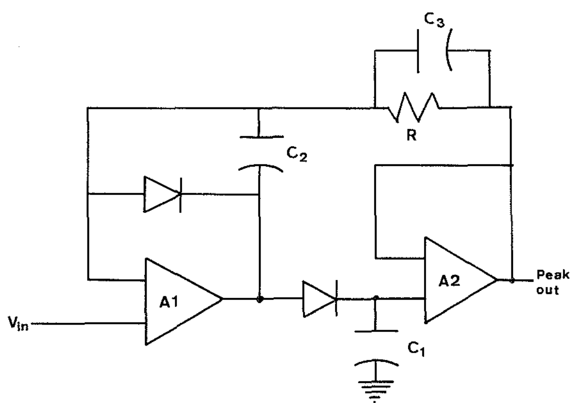

Figure 3. A noninverting peak hold circuit from Graeme et al. (1971). Two amplifiers are used in noninverting configurations.

INTEGRATION

A second useful function for bioluminescence assays is signal integration. While analog methods can give a good integration on short time scales (Philbrick/Nexus Research, 1969), digital methods are best for long term integration. A convenient and easy method of integration is to convert a signal voltage into a pulse train and then simply count the pulses. Since linear voltage-to-frequence converters are now available in modules similar to op-amps, this circuitry is easily implemented (figure 4).

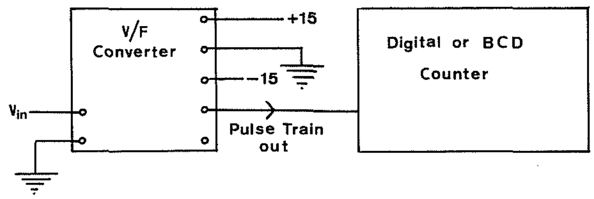

Figure 4. Using a modular voltage-to-frequency converter to drive a counter for signal integration.

POWER SUPPLIES

Most operational amplifiers require ±15-V power supplies. These are now available in a variety of modules. Many of the op-amp manufacturers also offer power supplies. Digital logic requires +5 V, also available in modules.

The only remaining power requirement is that of the photomultiplier. Several manufacturers make small modular d.c.-to-d.c. converters which will convert low voltage d.c. into the high voltage d.c. necessary for the photomultiplier. RCA has recently introduced integrated photomultiplier modules (C350001C/PF1004C Integrated Photodetection Assemblies) containing the photomultiplier, dynode chain, and power supply integrated into a single package. Generally, d.c. converters can be powered by the +15-V power supply used for the op-amps.

A GENERAL PHOTOMETER CIRCUIT WITH RATIO CAPABILITY

The circuit in figure 5 was designed for both general bioluminescence assays and for a specialized assay involving detection of the ratio of blue light to green light in coelenterate in vitro assays (Wampler et al., 1971; 1973). Here we use an autoranging digital voltmeter (Datel DM2000AR*) as a read-out device, a voltage-to-frequency converter-integrator circuit, and a multiplier-divider module to obtain the ratio. Table 1 lists the parts for this instrument. Signals 1 and 2 for the ratio assay are obtained from a detector module (figure 6). For regular assays with low light levels, an end window tube (EMI 9635B) is used. In this case the power supply is a d.c.-to-d.c. converter (PMSI-3A†). The housing for this detector (figure 7) is machined from

* Datel Systems, Inc., 1020 Turnpike Street, Canton, Massachusetts.

† Del Electronics, Mt. Vernon, New York.

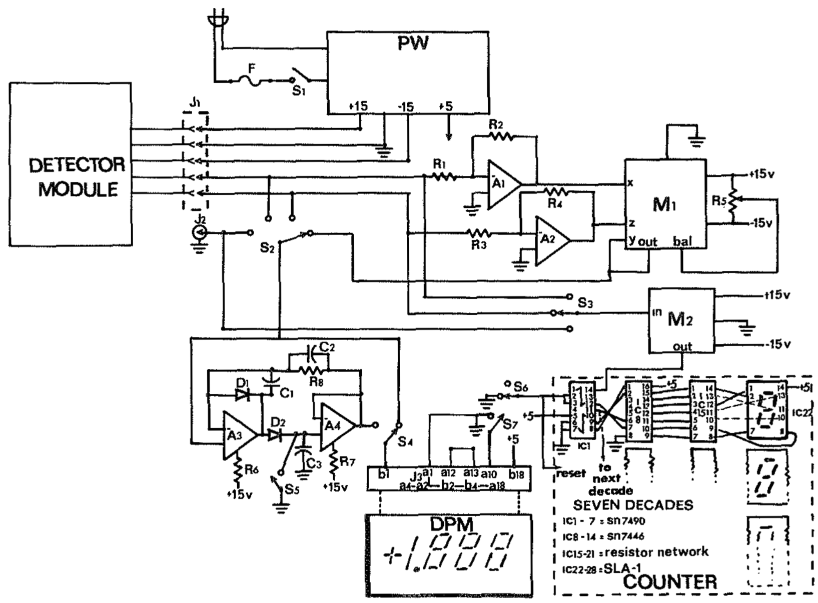

Figure 5. Circuit diagram of photometer. The parts and the values of the components are in table 1.

aluminum with a planar shutter to allow close proximity between the tube face and the sample.*

The signals from the photomultiplier tubes are transduced by the circuit of figure 7, and the output signal of the op-amp is transmitted to the read-out instrument via a multiconductor cable which also acts to carry the ±15-V power to the detector. Switch S_2 allows the digital voltmeter (DVM) to measure the signal from either photomultiplier or the ratio from the 426A module, and S3 allows integration of either signal 1 or signal 2. With S4, the peak hold function can be selected for display on the meter instead of intensity. S5 resets the peak circuit while S6 resets the integrator. The DVM and the integrator can also examine an input signal from other voltage sources using the front panel BNC connector marked TEST.

For the ratio measurement, using the 426A module, the denominator must be larger than or equal to the numerator and both must be negative for a positive output; the output signal read by the DVM is 10 X signal 1/signal 2. Because signals 1 and 2 are positive voltages, they must be inverted. The inverting amplifiers, A1 and A2, are integrated circuit op-amps with precision resistors for unity gain. For the best measurement, the high voltage of tube 2 should be adjusted until signal 2 is near 10 V, then signal 1 adjusted to an appropriate value.

* Faini, G. L., unpublished, 1975.

Table 1

Parts List

Symbol	Item and Source or Description	Approximate Cost
Read-out Chassis:		
A1 and A2	741 Integrated circuit op-amps	$ 2.00/ea
A3 and A4	Analog Devices 40J—FET input general-purpose op-amps: Analog Devices, Inc., Cambridge, Mass.	$ 12.00/ea
C1 and C2	0.1 μF capacitors	---
C3	0.47 μF capacitor—selected low leakage capacitor	$ 5.00
D1 and D2	diodes	---
DPM	Autoranging digital panel meter: Datel Systems, Inc., Canton, Mass.	$160.00
F	3 amp fuse	---
IC_1-IC_7	SN4790 decade counter	$ 1.00/ea
IC_8-IC_{14}	SN7446 seven segment driver	$ 1.00/ea
IC_{15}-IC_{21}	Allan Brady 7443 or similar 150 Ω resistor array	$ 2.00/ea
IC_{22}-IC_{28}	OPCOA SLA-1 LED display: OPCOA, Edison, New Jersey	$ 2.00/ea
J_1	5 pin military connector	$ 5.00
J_2	BNC connector	---
J_3	P.C. board connector supplied with DPM	---
M1	Multiplier module 426A: Analog Devices Inc.	$ 45.00
M2	Voltage-to-frequency converter 4701: Teledyne Philbrik, Dedham, Mass.	$ 60.00
PW	Model 2R-70T triple power supply I15: +5 V d.c. power tec, Chatsworth, Calif.	$110.00
R1-R4	10K, 0.1%, ¼ W resistors	---
R5	20K trim pot	---
R6 & R7	500 Ω, 10%, ¼ W resistors	---
R8	100 K, 1%, ¼ W resistors	---
S1	5 amp, lighted push button switch	$ 3.00
S2	4 position rotary switch	---
S3	3 position rotary switch	---
S4	SPDT toggle switch	---
S5 & S7	Normally open momentary push button switch	---
S6	Normally closed momentary push button switch	---
Miscellaneous:	Wire, cables, sockets, chassis, power cord, and so forth	
Detector Module 1:		
PM_1 & PM_2	RCA integrated photodetector assemblies	$120.00/ea
A_5 & A_6	Chopper stabilized op-amps model 233J: Analog Devices, Inc.	$ 60.00/ea

Table 1 (continued)

Symbol	Item and Source or Description	Approximate Cost
Detector Module 1 (continued):		
R_9 - R_{12}	10K, 10-turn potentiometers	$ 6.00/ea
R_{13} - R_{14}	10 MΩ, 1% resistors	--
R_{15} - R_{16}	10 MΩ resistors	--
C_4 & C_5	0.01 μF capacitor	--
B	Beam splitter: Edmund Scientific Co., Barrington, N.J.	$6.00 - $20.00
Detector Module 2:		
PM_3	EMI 9635 B photomultiplier: Gencom Division, Plain View, N. Y.	$205.00
PW_2	High voltage power supply–d.c.-to-d.c. converter–PMSI-3A: Del Electronics, Mt. Vernon, N. Y.	$ 90.00
A_7	Low bias FET op-amp Model 1029: Teledyne Philbrick, Dedham, Mass.	$ 45.00
R_{17}	1000 ohm, 10-turn potentiometer	$ 6.00
R_{18}	10 MΩ resistor	--
R_{19}	10 K, 10-turn	$ 6.00
R_{20}	50 K trim potentiometer	--
R_{21}	100 MΩ, 1% resistor	--
C_6	0.001 μF capacitor	--

All calibration adjustments can be performed from the front panel using the TEST input. The bezel of the meter conceals its internal offset, gain, and zero adjustments. No adjustments are required of the integrator circuit or the peak hold.

The Datel DVM is autoranging, that is, it shifts between read-out ranges of 199.9 mV, 1.999 V, and 19.99 V full scale as the signal input dictates. The meter's hold function, S7, allows leisurely reading of a value, and with three and one-half significant figures and three scales, the range of light measurements for a particular high voltage setting is greater than 10^4 for a reading of three significant figures.

The time constant on the detector current transducers (figure 7) is 0.1 s and a chopper stabilized op-amp was chosen to minimize long term drift. Changing the feedback resistor R would also change the gain, and switchable values could be used to increase the dynamic range of the instrument for a fixed voltage setting.

The power supply chosen, while not as compact as some available, has considerable current output capabilities and is cheaper than less powerful, but smaller, potted modules.

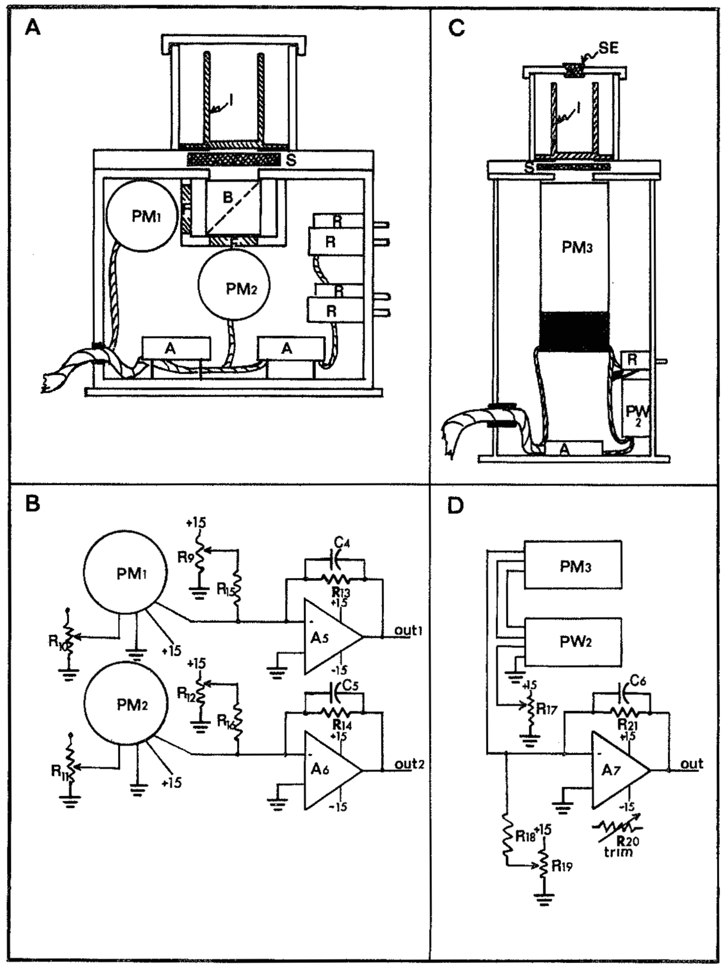

Figure 6. Diagram of the detector assemblies. A. The two-photomultiplier assembly used to assay the ratio of blue light to green light in coelenterate bioluminescence. In this instrument, B is a beam splitter, S the planar shutter mechanism, and the filters F are interference filters (470 nm for the blue component and 510 nm for the green one). B. The circuit of Assembly A. C. The single photomultiplier assembly. D. The circuit diagram of Assembly C. The electronic parts used in these instruments are detailed in table 1. I is a lucite insert used to hold specific assay vials, SE a syringe septum, and S the planar shutter.

The choice of component values in the peak hold circuit allows tracking of a full scale change (0 to 10 V) with a rise time of less than 10 ms. Capacitor

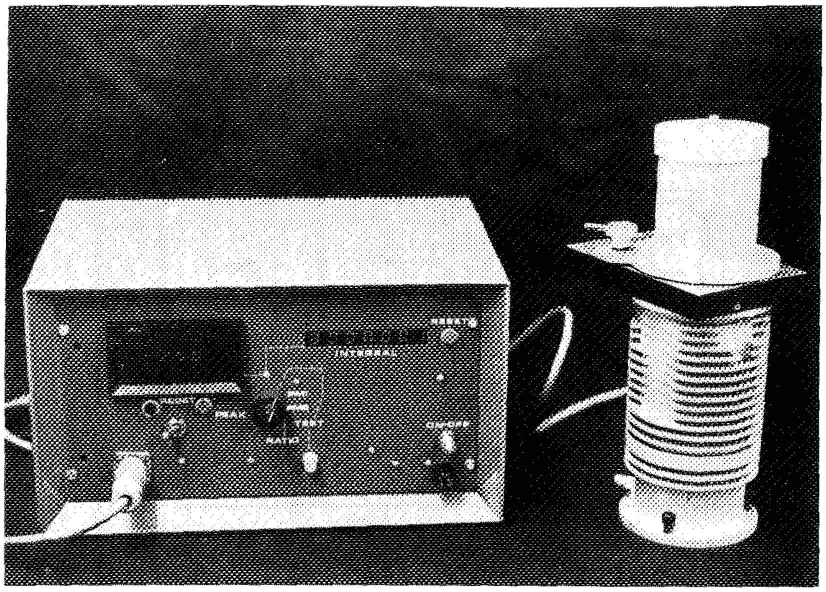

Figure 7. The complete read-out chassis and the single photomultiplier detector.

C_3 was selected from among several of its type for its low leakage. The decay of the peak value varied from 10 percent decay in a few seconds up to 30 min for the same change with different low-leakage capacitors. The socket for the op-amp A4 of this circuit should have well insulated terminals to prevent leakage.

While a printed circuit board could easily be made for this circuit, with the number of components involved, point-to-point wiring is easy and convenient, particularly if all amps and modules are mounted in sockets. Soldered connections were used except in wiring the counter. For the many interconnections of the counter and to facilitate packing, it was wired by wirewrap technique using wirewrap pin sockets and 30-gage Teflon insulated wire.

VARIATIONS OF THE BASIC DESIGN

For some measurements certain changes in the circuit of figure 5 might be made. A timed integration might be useful for some assays. A simple digital timer (Collins, 1974) could be arranged to gate the integrator on and off at preset times. Another variation would be to incorporate the voltage-to-frequency converter into the detector housing and then transmit the light intensity information as a pulse train. This would allow long distance transmission of the luminescence information in field applications where the detector cannot be near the read-out device, such as in a probe for underwater luminescence.

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