Techniques of Low Level Light Measurement

There are Several Methods of Measuring and Analyzing Light

The measurement of light is critical to a broad spectrum of experimental situations. Spectroscopy, astronomy, laser spectral analysis, and fiberoptic cable characterization are but a few of the areas where the precise measurement of light is critical. High intensity light levels can be measured with a minimum of effort, but as the levels approach the experimental interference of noise, measurement requires special techniques to provide the necessary accuracy and precision.

Low level light measurements are required in an ever increasing number of areas. In many cases, interference and noise make the recovery and measurement more difficult. With a basic understanding of the actual information required and the techniques available, one can call upon a broad range of techniques and commercially available instrumentation. This article will discuss the characteristics of light and its measurement even in the presence of large levels of interference or noise. The techniques of photon counting, DC electrometers, lock-in amplifiers, boxcar and multipoint averagers, and optical multichannel analyzers will be discussed.

The Problem

For our purposes, light can be considered in terms of photons, packets of energy with zero rest mass. The higher the light level, the more of these energy packets are available. And the higher the wavelength, the lower energy each packet will be. As the level of light, and therefore the photon rate, decreases, it becomes more susceptible to interference from random events and noise from many sources. Figure 1 shows the many sources of interference which can make the recovery of a low light level tedious or difficult. The typical 1/f curve consists of a variety of unusual sources not usually taken into consideration. Elevator noise, which may have a period of several minutes; shift and class changes, with hourly periods; and even annual temperature variations all make up the familiar 1/f curve, which becomes most pronounced as frequency approaches zero, or DC.

Detectors

The most general-purpose light detector—and one of the most common—is the photomultiplier tube. Although a variety of detectors are available, we shall limit our discussion to photomultiplier tubes (PMT).

Figure 2 shows a schematic representation of a PMT. Photons impinging on a photocathode generate photoelectrons. An internal electric field directs these photoelectrons to a series of dynodes. Each dynode generates a number of secondary electrons for each photo electron striking its surface. After passing a series of these dynodes, the number of electrons has been multiplied by a factor of 10^3 to 10^8, depending on the tube configuration and the number of dynodes. Thus, for each

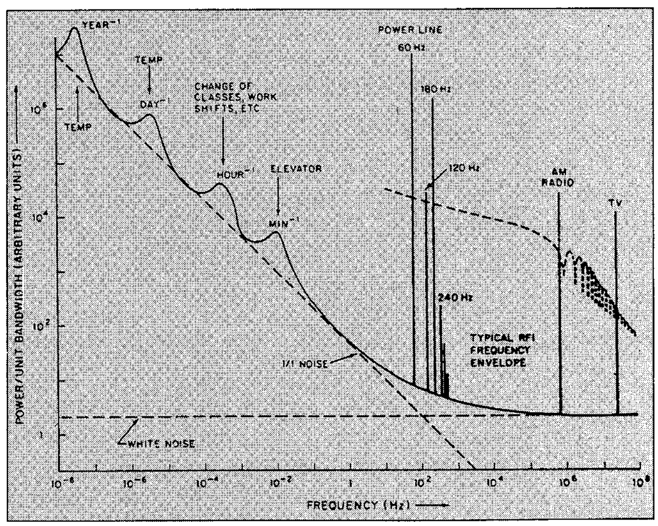

Figure 1. Some of the many sources of interference compounding the measurement of low levels of light.

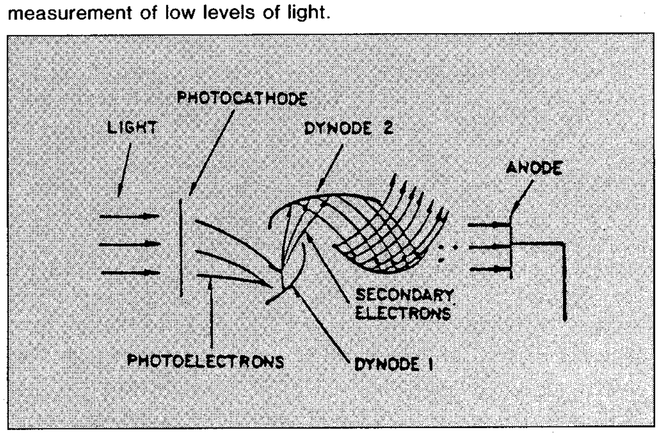

Figure 2. Schematic representation of a photomultiplier tube and its operation.

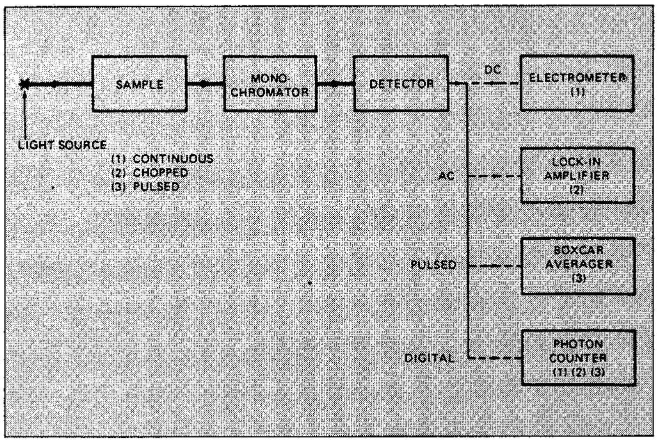

Figure 3. Methods of measuring bursts of output currents from a photomultiplier tube.

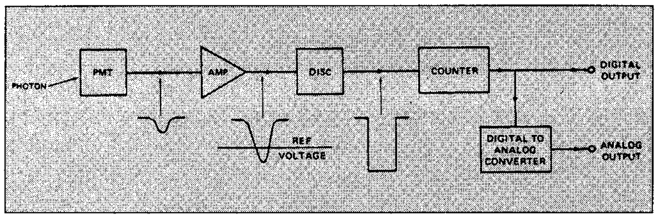

Figure 4. Schematic diagram of a typical photon counting system.

photon striking the photocathode a burst of electrons outputs at the PMT. These bursts of electrons result in a current given by:

$$I_{anode} = A_{pmt} \times q \times e \times Rp$$

Where

A_{pmt} = Photomultiplier tube gain
I_{anode} = Anode current in amperes
q = Quantum efficiency of the PMT
e = Charge on an electron
Rp = Photon rate in photons/second

The bursts of output current can be measured using several techniques, as shown in Figure 3. A photon counting technique can count the number of individual output bursts per unit time. Alternatively, an integrator can smooth the current bursts and measure the average output current. The second technique is further subdivided into DC measurements using an electrometer, chopped or modulated techniques using a lock-in amplifier, or pulsed techniques using a multipoint averager or boxcar integrator to measure the resultant waveform.

Photon Counting Method

A typical photon counting system is shown in Figure 4. A photon hitting the photocathode results in a current burst out of the PMT as described earlier. This pulse is amplified and fed to a discriminator. The function of the discriminator is to disregard all pulses below a selected value, treating such events as noise and not photon pulses. This reference or discriminator level can be operator or factory selected depending upon the system.

In more sophisticated systems, a dual level or window discriminator is used. Whereas a single level discriminator provides one output pulse for all current bursts above the reference set point, a dual level discriminator can function in either a window mode or in a correct mode. In the window mode all current bursts higher than the upper level are disregarded. Such bursts are assumed to result from a high energy pulse at the PMT cathode, and not a photon. In the correct mode, all bursts higher than the upper discriminator are counted as two pulses. They are assumed to result from multiple photons arriving at the PMT cathode simultaneously.

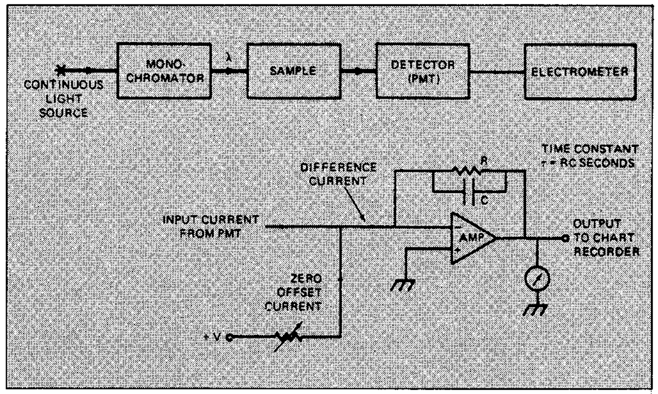

Figure 5. A current measuring electrometer system.

The output of the discriminator is a standard pulse of constant amplitude and duration, which can be fed into a counter. The digital count can be displayed in photons per second on a digital meter or, after conversion to a DC level in a digital-to-analog converter, it can be fed to an analog recorder. This is the most basic photon counting system. A number of refinements can be made to the system. For example, a ratiometer technique can compensate for source variations and a subtraction mode can eliminate a background.

The photon counting method is among the most sensitive light measurement techniques available. For the same reasons, however, it is among the most sensitive to interference. Extremely well shielded tube housings and systems are required to eliminate radio frequency interference. Care must also be taken to guard against stray light from any source entering any part of the tube or the experimental cell. In summary, photon counting offers an extremely sensitive light measuring technique capable of measuring over a wide range of light levels. Its susceptibility to interference, however, limits its use to only the most highly shielded and light-tight experiments. Modulation techniques used with photon counting can eliminate background noise but the sensitivity to interference continues to be a major limitation.

DC Measurement Techniques

Figure 5 shows a typical current measuring electrometer system that reads the output of a PMT. The PMT output current is integrated with a time constant equal to the value RC in the feedback of the operational amplifier. The output voltage of the electrometer is proportional to the average input current. Although simple and straightforward, the electrometer is a DC or zero frequency system. As such, it is extremely susceptible to 1/f noise, stray light, and dark current and leakage current in the tube. Many electrometers have zero offset controls which allow this dark current to be offset but this cannot offset the noise or AC component of the noise.

Although extremely low-cost and simple, the DC technique is susceptible to innumerable noise and interference sources. Since there is no discrimination against

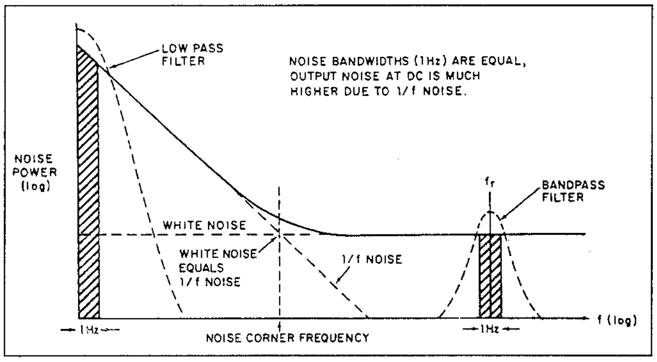

Figure 6. By moving the signal away from noisy low frequency regions, a low level detected light signal can be recovered.

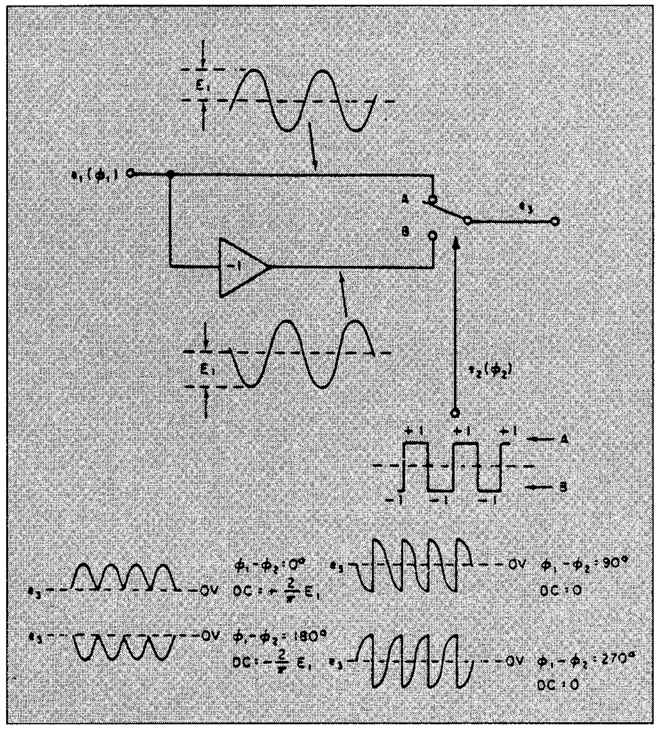

Figure 7. With the phase-sensitive amplifier technique, the center frequency of the narrowband amplifier is locked to the modulation frequency.

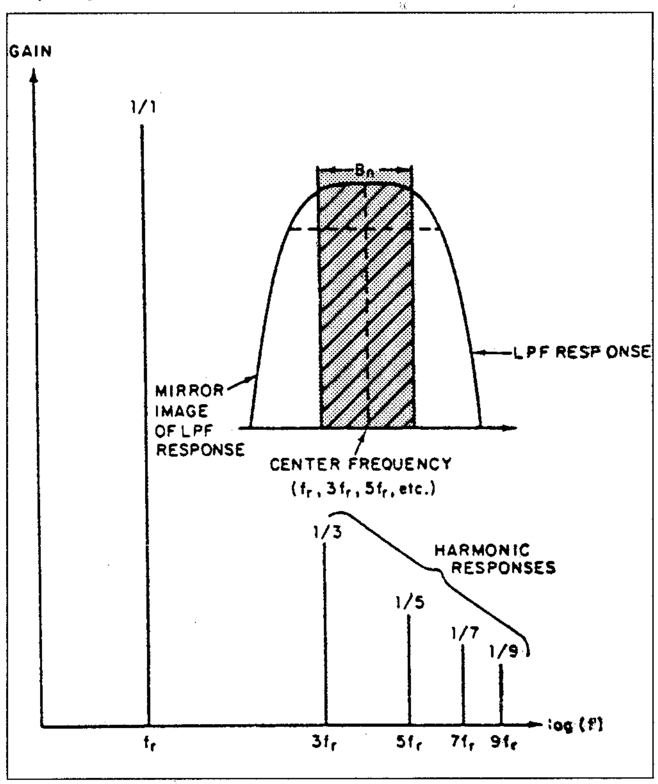

Figure 8. Frequency response of a phase-sensitive detector.

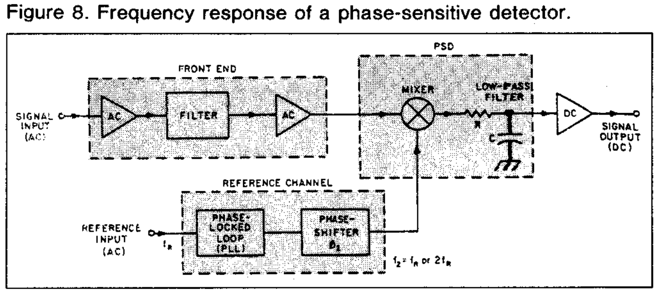

Figure 9. Block diagram of the basic lock-in amplifier.

these sources, the electrometer technique is the least desirable of all the various low level signal recovery techniques.

The Lock-In Amplifier Technique

One of the most popular methods to reduce noise and recover a low level detected light signal is to modulate the signal. As shown in Figure 6, the signal is moved in frequency from the noisy 1/f area at zero frequency to a less noisy area at some arbitrary frequency f_m. Conventional tuned amplifiers can be used up to a point to limit noise and provide a narrow passband about the modulation signal. Tuned amplifiers, however, are noisy by nature and become unstable as the selectivity *(Q)* is increased. Selectivity is defined as the ratio of the center frequency (f_m) to the 3dB bandwidth (f_{3dB}). A *Q* of 100, or a 1% bandwidth, is the highest practical limit for a narrowband tuned amplifier to recover a low level signal.

An extension of the narrowband system is the lock-in amplifier or phase sensitive amplifier technique. This type of system locks the center frequency of the narrowband amplifier to the modulation frequency, allowing increased narrowbanding without the instability normally associated with tuned amplifiers. The heart of all phase sensitive detectors is best described by considering Figure 7. The signal of interest is fed in parallel to inverting and non-inverting unity gain amplifiers. The output of these two amplifiers is selected by the switch position as determined by the polarity of a reference signal (f_r). If we consider the waveforms, we can see that if the signal frequency and the reference frequency are in phase, the output will be a maximum positive level. Signals shifted in phase by 90°, 180°, and 270° provide output waveforms and levels as shown. The RC filter integrates or smooths the signal to provide a DC level which is proportional to the average value of the phase-sensitive detected signal.

The overall transfer function, therefore, of a simple phase-sensitive circuit is $E_o = E_i \phi$, where E_o is the output voltage, E_i is the input voltage and ϕ is the phase shift between the input signal and the reference signal. The effect of harmonic frequencies on the output of the phase-sensitive detector is shown in Figure 8.

In order to remove the harmonics of the signal, tuned amplifiers or heterodyning systems are used. Low noise preamplifiers matched for minimum noise performance are normally supplied at the front end of the

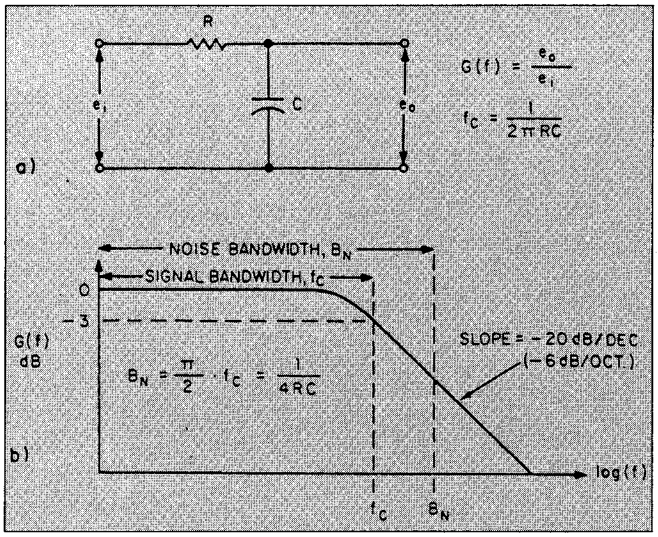

Figure 10. Noise bandwidth is determined by the time constant of the RC filter.

lock-in amplifier. Figure 9 is a block diagram of a basic lock-in amplifier.

In essence, the phase-sensitive technique consists of four steps:

1. Moving the signal of interest from zero frequency to an arbitrary frequency by modulating or chopping the light.
2. Amplification of the signal of interest at the modulation frequency.
3. Phase sensitive detection and demodulation of the signal.
4. Narrowing the bandwidth around the signal of interest by integration in the low pass filter (LPF).

The bandwidth of the lock-in amplifier can be made arbitrarily narrow by increasing the RC time constant. The 3dB signal bandwidth for a single section RC filter is the conventional $1/(2\,\pi RC)$. The roll off or attenuation rate is 6 dB/octave or 20 dB/decade. The bandwidth for noise considerations is somewhat different than for the signal. A concept of equivalent noise bandwidth (ENBW) is usually used to define the bandwidth for noise. ENBW is defined as the frequency below which the area under a flat response curve is equal to the actual area under the LPF response curve integrated from DC to infinite frequency, as shown in Figure 10. It is calculated by multiplying the 3dB bandwidth, $1/(2\pi RC)$, by $\pi/2$, for a single section RC filter. This yields an ENBW of $1/(4RC)$. For double section filtering with the same value of RC the ENBW becomes $1/(8RC)$. Using a time constant value of 100 seconds and dual section filtering the equivalent noise bandwidth is:

$$1/(8RC) = 1.25 \times 10^{-3} \text{ Hz}$$

With an operating frequency of 400 Hz the *Q*, or selectivity, is:

$$Q = f/f_{3dB} = 400/(1.25 \times 10^{-3}) = 320 \times 10^{3}$$

The output of the lock-in amplifier is a DC level proportional to the signal. This can be recorded on a strip

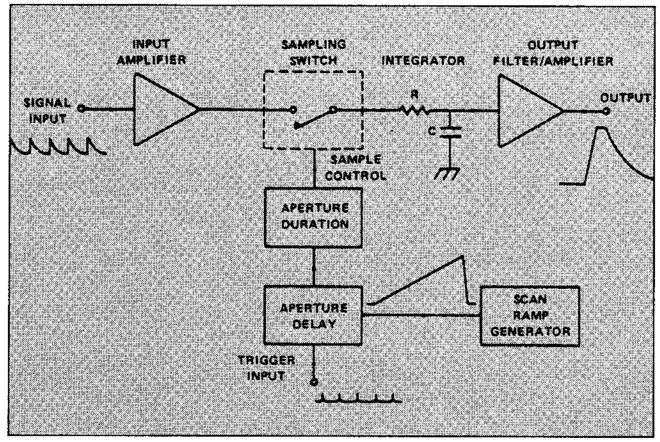

Figure 11. Schematic diagram of a boxcar averager in scanning mode.

chart or x-y recorder as a function of time or a second parameter such as wavelength or stress voltage.

Because of its narrow bonding capability the lock-in amplifier provides the most powerful signal recovery technique. Signals buried by over 300,000 times full scale noise can routinely be measured. However, the technique

The photon counting method is among the most sensitive light measurement techniques available.

requires a chopper or modulator for the signal, and because the signal is periodically turned off and on, there is some loss of signal. But this is more than compensated for by the ease of signal recovery and the overall capability of the technique. Recently introduced lock-in amplifiers incorporate microprocessor control and IEEE-488 and RS-232 interfaces, allowing use in industrial production and long term research applications.

Waveform Averager

The amplitude of the recovered light signal is often sufficient. There is, however, a large group of experiments where the information of interest is contained in the shape or duration of the light signal or in the amplitude of a narrow repetitive pulse with poor duty factor. Fluorescent decay measurement, optical time domain reflectometry, and time resolved spectroscopy are but a few of these applications. The optical exciting source is normally a short duration pulse of light which causes an output from the sample under test at the same or a different optical wavelength.

Figure 11 shows a simplified single channel averager, also known as a boxcar averager. The input signal is amplified and fed into a switch, whose output goes to an RC exponential averager. The trigger, usually developed from the experimental exciting source, determines the timing for closing the switch. Settings for internal delay and gate closing durations are selected in the boxcar averager. The duration of the switch closing is short relative to the RC time constant of the low pass filter.

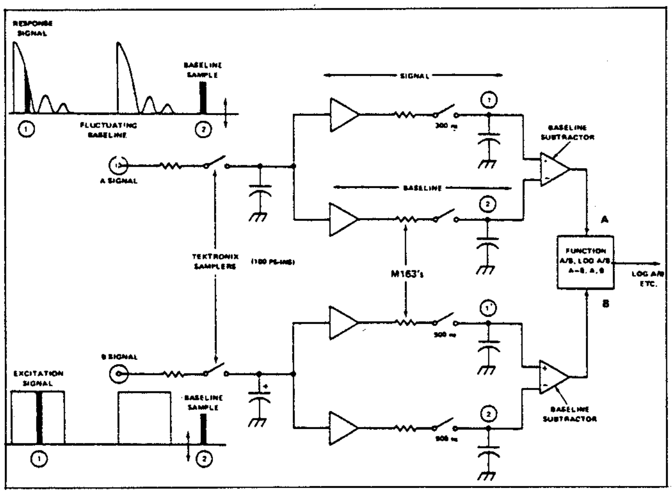

Figure 12. Diagram of a dual-channel boxcar averager.

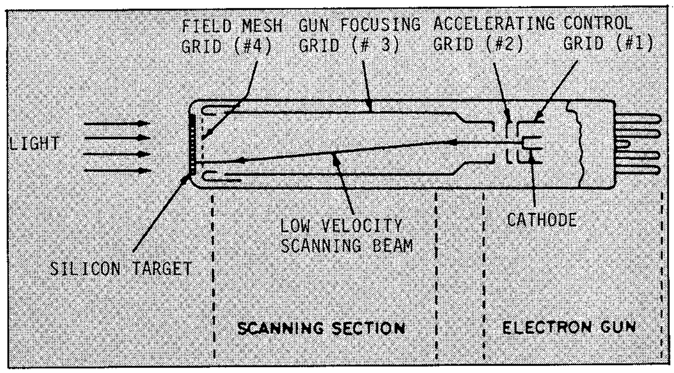

Figure 13. Cross section of a typical vidicon tube.

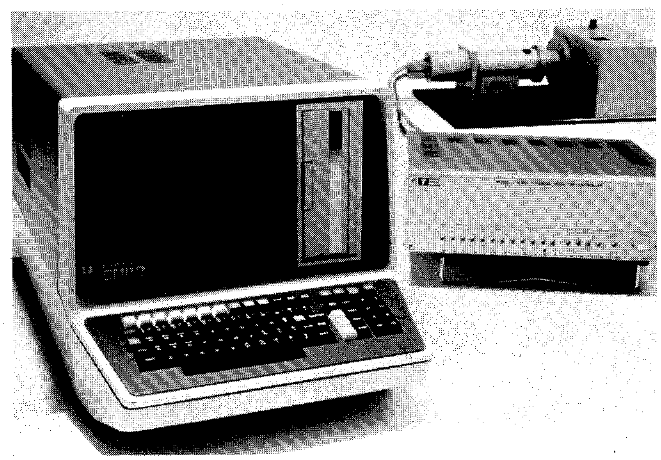

Figure 14. Typical configuration of an optical multichannel system.

With each subsequent input, the signal stored in the capacitor increases until it approaches the average value of the input signal, while the noise is attenuated by the low pass filter. Signal-to-noise improvement is typically proportional to the bandwidth reduction provided by the exponential averager. The effective time constant must be multiplied by the duty factor of the opening when calculating the observed time constant.

Commercial boxcar integrators are capable of sampling with openings (or gates) of less than 100 picoseconds. Built-in gate scan circuits allow the boxcar integrator to scan slowly across a repetitive waveform of interest and reduce the overall noise. Dual-channel boxcar averagers, as shown in Figure 12, allow the baseline to be sampled and subtracted from the signal of interest to eliminate baseline drift, a frequent source of error in sampled measurements. When the sampling time required reaches the microsecond level, multipoint averagers become more efficient in recovering waveforms. A number of gated averagers can be cascaded and their sampling gates closed sequentially in time across the signal waveform. The efficiency of a multipoint system lies in its ability to sample the entire waveform on each trigger. A 1,000-channel signal averager would recover a signal 1,000 times as fast as a single channel system scanning across the signal. Although we have shown only analog averagers here for simplicity, recently developed boxcar averagers feature up to four simultaneous inputs, microprocessor and computer control, as well as data storage and manipulation. Such expanded capabilities extend the uses of these devices to a wide range of high speed industrial and research applications.

Optical Multichannel Analyzers

Until now our concern has been measuring a signal using a single detector. Where a spectrum was required, a monochromator was scanned and the output recorded as a function of wavelength. In many cases, it is necessary to measure a complete spectrum with all wavelengths of interest measured simultaneously. One way to do this is to disperse the information across a photographic film using a prism or polychromator. Although this method has been used for a number of years, it provides little quantitative information on the measured spectra.

An electronic equivalent of the photographic film is known as an optical multichannel analyzer (OMA). Film is replaced by a silicon target vidicon tube or diode array. Figure 13 shows a cross section of a typical vidicon tube. The silicon target shown on the left is a wafer of silicon on which a large number of photodiodes have been deposited. Photons striking these photodiodes generate electron hole pairs which in turn, decreases the charge stored in the diodes. The more light, the more photons, and the greater the decrease in charge.

An electronbeam scanned across the rear surface of the wafer replaces the charge lost due to the photons impinging on the diodes. By measuring the beam current as a function of wafer position, the spatial intensity of the light can be read. Since the target has memory, the light source can be turned on and off, or flashed, and the information then read and recorded. This is particularly useful in applications such as flashlamp quality control and time resolved spectroscopy.

In addition to the vidicon tube, linear photodiode arrays are becoming widely accepted as detectors for optical multichannel systems. Their higher sensitivity and resolution make them more applicable to the detection requirements of fluorescence and Raman spectroscopy. Figure 14 shows a typical display provided with such a system. Systems using the OMA technique feature microprocessor control, internal memory, and CRT readouts. Specialized systems are also available for such applications as plasma monitoring in the semiconductor industry. ●

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