Exp. 11
Measurements of Noise Equivalent Power FOR SILICON DETECTOR

Object:
To identify the noise equivalent power for silicon detector (p-n) junction for determine range of the electro optic spectrum.

Equipment:

1-Digital D.C power supply (2 amp).
2- Kethly device
3-Silicon detector operates on the spectrum range (400nm-1100nm) fixed on thermal distribution base
4-Digital voltmeter.
5- Metal jag contains monochromatic optical transmitters ( LED ) which are equal in power and with the following wavelengths:

(420nm, 560nm, 630nm, 850nm, 1000nm)

Theory:

The responsivity defined above gives a measure of how much output you can expect from a given detector for a specified input. For many laser applications, the signal is much larger than any noise source that may be present. The responsivity alone is adequate to characterize detector performance. But in many other situations you must detect a small signal in the presence of noise. For example, in optical fiber telecommunications, you must detect a laser signal after it has traveled many kilometers through the fiber. The available signal may not be much larger than the noise sources. You must distinguish the signal from the random fluctuations that make up the noise. In this case, other detector parameters become more important than the responsivity.
One such parameter is the noise equivalent power (often denoted NEP). The NEP is the radiant power that produces a signal voltage equal to the noise voltage from the detector.

Before we describe the NEP in detail, let’s discuss noise sources in photodetectors. Noise is a rather profound subject. In this module we can do little more than present the fundamental ideas and apply them to photodetectors. Noise can be any undesired signal. It can be divided into two broad categories: externally induced noise, and internally generated noise. External noise, as the name implies, includes those disturbances that appear in the system as a result of an action outside the system. Two examples of external noise are hum picked up from 60-hertz power lines and static caused by electrical storms. Internal noise, on the other hand, includes all noise that’s generated within the system itself. We now know that every resistor produces a discernible noise voltage and every electronic device (such as vacuum tubes and semiconductor elements) has internal sources of noise. You can think of internal noise as an ever-present limit to the smallest signal that the system can handle. The NEP is related to the internal sources of noise generated within the photodetector.

The first thing to note about noise is that it can’t be described the same way as the usual electrical voltages or currents. It’s common to think of a current or voltage in terms of its behavior with time. For example, we think of a sine wave as periodically varying with time, a direct current as being constant with time, and so on. Now, let’s look at the noise output of any electrical circuit as a function of time. We’ll find that the result is completely erratic. That is, we can’t predict what the amplitude of the output will be at any specific time. Also, there’ll be no indication of regularity in frequency in the waveform. When completely unpredictable conditions such as this exist, the situation is described as random.

A record of the output from a random noise generator might look like that shown in Figure 1. Figure 1 is a graph of the instantaneous voltage as a function of time. Because of the random nature of the noise, the voltage fluctuates about an average value $V_{av}$. How can you describe these fluctuations? A simple average is
meaningless, since the average of the variations is zero. Rather, it’s convenient to use the average of the squares of the deviations about \( V_{av} \). The average is taken over a time interval \( T \) that’s much longer than the period of the fluctuations. Equation 3 shows this mathematically.

![Instantaneous Voltage vs Time]

**Fig. 1**
A record of random noise voltages.

\[
\overline{\nu^2} = \overline{(V - V_{av})^2} = \frac{1}{T} \int_0^T (V - V_{av})^2 \cdot dt
\]

\( V = \) Value of voltage at time \( t \).

where:

\( \overline{\nu^2} = \) Mean-square voltage fluctuation.

\( \sqrt{\overline{\nu^2}} = \) Root-mean-square voltage fluctuation.

The right side of this equation contains an integral sign with limits 0 to \( T \). This simply means that you add all values \((V - V_{av})^2\) for each small increment of time \( \Delta t \) in the interval from time \( t = 0 \) to time \( t = T \).

You probably wouldn’t calculate the noise voltage directly from this equation unless you went through a laborious process. The important thing, though, is how this voltage is properly
measured. What about measuring the noise voltage? What kind of meter do you use? A true-rms meter is the best type for making noise measurements. It takes sophisticated circuitry to square the point-by-point voltage along one cycle of the waveform and then extract the square root of the average value of the squared quantity. Meters of this type include the so-called electrodynamometer. This class of meter was, at one time, the only one that would give an accurate reading of the rms values of a nonsinusoidal waveform such as that generated by random noise.

This is, however, no longer true. Many relatively inexpensive digital voltmeters and digital multimeters are now available with a true-rms option. Recent advances in microchip technology have made this possible. You must, however, always be careful in choosing a meter for noise measurements to ensure that the meter has a true-rms option. The standard laboratory meter (or VTVM) is less expensive. It’s usually an average-responding meter. If it’s used to measure noise, the meter reading must be multiplied by a correction factor. The correction factor depends upon the specifics of the noise. It won’t be discussed here.

A complete list of all types of noise is beyond the scope of this module. The following types of noise are those most likely to be found in a visible photodetector system:

a. **Johnson Noise**: Any resistor acts as a generator of noise that is called Johnson noise. The mean square noise voltage is directly proportional to the value of the resistance. Johnson noise is sometimes called thermal noise. It occurs in all conducting materials. It’s a consequence of the random motion of electrons through a conductor. The electrons are in constant motion, but they collide frequently with the atoms or molecules of the substance. Each free flight of an electron constitutes a minute current. The sum of all these currents taken over a long period of time must, of course, be equal to zero. But their ac component is Johnson noise.

b. **Shot Noise**: The term "shot noise" is normally associated with vacuum tubes in which the stream of electrons creates a noise due to the random fluctuations in the rate of arrival of electrons at the anode. This noise may be likened to the noise of a hail of shot
striking a target. Hence the name shot noise.

Shot noise is present in all photon detectors due to the random arrival rate of photons from the source of radiant energy under measurement and background radiation. This shot noise is often called "photon noise." Photon noise is the true ultimate limitation to detector performance. Even if all internal noise sources were eliminated, photon noise would set the ultimate limit for detector performance.

In semiconductor diodes and photomultipliers, the shot noise associated with the random generation of carriers is the major noise source. In photoconductors the major source of noise is associated with both the generation and the ultimate recombination of the charge carriers. That is, it’s associated with the fluctuations in the rate at which charge carriers are generated and recombine. It’s often referred to as generation-recombination (g-r) noise.

c. Excess Noise: At low frequencies, there are many types of noise for which the noise power varies inversely with frequency. A common term for this type of noise is 1/f (pronounced one over f) noise. It’s also known as excess noise since it exceeds shot noise at frequencies below a few hundred cycles. A variety of names are used to designate the 1/f noise associated with specific devices. It’s called modulation noise in semiconductors such as transistors, diodes, and detectors; contact noise in carbon-type resistors and their electrical contacts; and flicker noise in vacuum-tube cathodes. There are no simple mathematical expressions to describe these types of noise. In fact, some are not well understood to this day.

The important consideration about these sources of internal noise is that any one or a combination of the noise currents will determine the lower limit of detectability of a photodetector system.

Now we have a basic foundation on the subject of noise. We can discuss how manufacturers of photodetectors rate their devices in terms of noise. This lets us compare different types of detectors based on their noise equivalent ratings.

The amount of optical power incident on the surface of a photodetector that produces a signal at the output of the detector just equal to the noise generated internally by the detector is the noise equivalent power (NEP). This is usually the minimum
detectable signal level. (Signal-to-noise ratios less than 1 can be useful under some circumstances). Since, under these conditions, the signal power is equal to the noise power, we can say the signal-to-noise ratio is equal to one. Another equivalent way of stating NEP is to take the ratio of the total noise current to the responsivity at a particular wavelength. To calculate the signal-to-noise current ratio*, we need to know the output current produced by the radiation incident on a given area of the photodetector and also the noise currents from all sources. Recall that the major sources of noise are thermal and shot noise and that noise currents or voltages can’t be added but that noise powers add directly. We can calculate the rms value of signal current from the following equation:

\[
\text{signal} = \text{R} \ E_e \ A_d \\
\text{signal} = \text{rms value of signal current at the output of the photodetector.}
\]

where:

- \( R \) = Responsivity of detector in amps/watts at the wavelength of the incident radiation.
- \( E_e \) = Irradiance of incident radiation in watts/cm\(^2\).
- \( A_d \) = Irradiated area of photodetector, in cm\(^2\).
Fig. 2
Spectral response of silicon photodiode OUTPUT.

Given:
EXAMPLE A: INCIDENT RADIATION VERSUS PHOTODETECTOR RMS CURRENT
A photodetector with a spectral response similar to that shown in Figure 3. Radiation of wavelength 0.7 microns and irradiance of 100 microwatts/cm² is incident on a 0.5-cm² area of detector surface.

Find: The rms value of signal current at the output of the photodetector.

Solution:
From the spectral response curve, we determine that the value of R is 0.4 A/W at a wavelength of 0.7 μm. Using Equation 4, we have:

\[ \text{signal} = (0.4 \text{ A/W}) (10^{-4} \text{ W/cm²}) (0.5 \text{ cm²}) = 20 \mu \text{ amperes} \]

In dealing with several sources of noise, obtain the total noise by taking the square root of the sum of the square of the individual noise components. That is:

\[ i_T = \left( i_1^2 + i_2^2 + \cdots + i_n^2 \right)^{1/2} \]

\( IT = \) Total noise current.

Where:
\( i_1, i_2, \ldots i_n = \) Noise currents of the \( n \) noise sources that contribute.
EXAMPLE B: PHOTODETECTOR CURRENT SIGNAL-TO-NOISE RATIO.

Given: A photodetector with rms signal current of 20 microamperes, a shot noise current of 2.27 picoamps, and a thermal (Johnson) noise current of 0.416 picoamps.

**Find:** Current signal-to-noise ratio of photodetector.

**Solution:**

\[
\left( \frac{S}{N} \right)_i = \frac{i_{\text{signal}}}{\sqrt{i_{\text{shot}}^2 + i_{\text{therm}}^2}} = \frac{20 \times 10^{-6}}{\sqrt{(2.27 \times 10^{-12})^2 + (0.416 \times 10^{-12})^2}} = 8.66 \times 10^6
\]

If we measure the total power into the photodetector from the radiant source at the point at which the current signal-to-noise ratio at the output of the detector is unity, we can calculate the NEP. For 

\[ \text{is} = R \Phi \ e \]

\[ \text{is} = \text{Signal current, rms value.} \]

\[ R = \text{Responsivity, amps/watt.} \]

\[ \Phi \ e = \text{Power incident on detector, watts.} \]
For the example given above:

\[ \frac{R \Phi_e}{(S/N)_i} = \left[ \frac{\sigma_{\text{shot}}^2 + \sigma_{\text{thermal}}^2}{\Phi_e} \right]^{1/2} \]

\[ \Phi_e = \left[ \frac{\sigma_{\text{shot}}^2 + \sigma_{\text{thermal}}^2}{R} \right]^{1/2} = \text{NEP} \]

\[ = \frac{5132 \times 10^{-24}}{0.4} = 0.4 \times 2.31 \times 10^{-12} \]

Note: \( R = 0.4 \, A/W \) at 0.7 \( \mu \) \( m \)

Thus, the \( \text{NEP} = 5.77 \times 10^{-12} \) watts

Note that the \( \text{NEP} \) normally is quoted by manufacturers using a measurement bandwidth of 1 hertz. The \( \text{NEP} \) increases as the square root of the measurement bandwidth.

It’s difficult to measure the signal when the signal-to-noise ratio is unity. So it’s customary to make the measurement at a high level of incident radiation and calculate the \( \text{NEP} \) from the following equation:

\[ \text{NEP} = \frac{E_e A_d}{V_s^2 / V_n^2} \quad \text{Equation 5} \]

\( \text{NEP} = \) Noise equivalent power in watts to produce a signal-to-noise (S/N) ratio of unity.

where:

\( E_e = \) Power density at surface of detector in W/cm\(^2\) .

\( A_d = \) Sensitive area of photodetector in cm\(^2\) .

\( V_s = \) rms value of signal voltage at output of detector.

\( V_n = \) rms value of noise voltage at output of detector.

This method assumes that the signal output of the detector is a linear function of the input radiation. This assumption is usually valid for S/N rations of 10\(^3\) or less.
A similar measure is often used to describe the performance of an entire system. It’s noise equivalent irradiance (NEI). NEI is the radiant flux density necessary to give an output signal equal to the detector noise. The NEI is given by the following equation:

\[
\text{NEI} = \frac{\Phi_o v_n^2}{v_s^2}\]

Equation 6

where: \(\text{NEI}\) = Noise equivalent irradiance in W/cm\(^2\) to produce an \(S/N\) ratio of unity at the output of the system.

When used to describe the performance of an entire system, NEI expresses the irradiance (W/cm\(^2\)) at the entrance to the detector required for an S/N ratio of unity at the output of the system electronics.

A typical NEP measurement is shown in Figure 3. Initially, the total noise voltage at the frequency of 1 kHz and bandwidth determined by the waveform analyzer is read on the true-rms meter with the source blocked off. Next, you increase the radiant flux until the output reading equals two times the first reading. The NEP of the system, including the amplifier and analyzer, is the value of radiant power measured in watts incident on the detector. This may be an extremely small value and, therefore, difficult to measure. So, you can get the voltage S/N ratio at a higher level of radiation and make use of Equation 5 to determine the NEP.
The noise contributions of the preamplifier and waveform analyzer are less than the noise from the photodetector. If they were less, we could determine the detector NEP by simply taking the ratio of the detector noise current in amperes to the responsivity in amps/watt.

A preferable technique for measuring the relative contributions of the detector, preamplifier and waveform analyzer to the noise is to measure the noise at the output of the waveform analyzer. Measure first with the detector connected in the normal manner. Then measure with the detector replaced by a low-noise resistor of the same value as the detector.

You will have to judge, on the basis of these measurements, whether it will be necessary to correct the values of detector noise read on the meter to eliminate the effects of noise contributed by the instruments.

Discussion
2. Describe the experimental setup for measuring NEP.
3. Explain the relationship between D* and NEP.