Noise in Photodiodes

Module 4

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Contents

1 Objectives

This module describes the noise sources present in a photodiode. Particular attention is paid to avalanche photodiodes, biased in avalanche mode, with excess noise (noise dominant in avalanche photodiodes) being explained. After studying this module, the reader will:

- Understand the two basic noise sources present in a photodiode, i.e., Johnson noise and thermal noise.
- Appreciate the existence of excess noise in avalanche photodiodes and understand the impact it has on photodiode performance.
- Understand the components of a noise equivalent circuit model and the concept of noise equivalent power.

2 Noise in Photodiodes

The notion of noise in a photodiode is an extremely important concept. Noise is generally an unwanted and undesirable component making up part of the overall "signal" measured by the detector. Usually the noise is a random fluctuation that is not related to the signal that we wish to measure. In the measurement of optical power the noise thus imposes a lower limit on the amount of optical power that one can measure with a particular detector. There are numerous optical detector types that we could explore, but here we limit ourselves to a discussion of noise in photoconductive, p-n junction and avalanche photodiodes. The main sources of noise that we will discuss are

- *Johnson Noise* - this is a thermal noise that represents noise power generated by thermally agitated carriers.

- *Shot-Noise* - this is a random fluctuation caused by the manner in which electrons are generated through interaction with incoming electromagnetic radiation.
- *Flicker-noise* - this arises from surface and interface defects and traps in the bulk of the semiconductor and is only important at very low frequencies, typically less than 1 kHz.
- *Excess-noise* - this is a noise source particular to avalanche photodiodes and it arises due to the statistical nature of the impact ionisation process that produces current gain in the device.

2.1 Johnson Noise

Johnson Noise, or sometimes called Nyquist Noise, is the term applied to describe fluctuations in voltage across a dissipative circuit element. The origin of these fluctuations is often attributable to thermal motion of the charge carriers. In a resistor the charge is neutral across the whole volume of the device, however, in a localised region there are charge gradients established by the random thermal motion of carriers in the region. If one connects a second resistance across the first resistance, the random fluctuations in voltage caused by thermal motion of the carriers will give rise to a current flowing in the circuit, thus transferring power to the second resistor. For a complete derivation of the mean square noise current due to Johnson noise the reader is referred to [1, 2, 3]. For the most part it is sufficient to realise that the mean square noise current depends on the absolute temperature, the magnitude of the resistance and the bandwidth of the signals of interest. The mean square Johnson noise current is given by:

$$\overline{i_J^2} = \frac{4kTB}{R} \tag{1}$$

where k is Boltzmann's constant, T is the absolute temperature, B is the signal bandwidth, and R is the resistance.

2.2 Shot Noise

Shot noise in photodiodes occurs due to statistical fluctuations in the photocurrent caused by the random arrival times of the photons (a quantised source) absorbed to create the e-h pairs.

If the quantised source has a large number, N, of independent emitters, each having a small probability, p, of emission, such that $Np = M$ is finite, then the source emission rate follows a Poissonian distribution. If n emissions are observed in a time interval, T, then n follows a distribution:

$$p(n) = M^n e^{-M}/n! \tag{2}$$

where M is the mean value.

The mean time between successive emissions is $\langle t \rangle = T/M$ with a distribution $p(t) = e^{-t/\langle t \rangle}$ and is independent of previous events. If the current is considered as a sequence of Dirac-delta pulses arriving at random times t_k, each having a magnitude q (i.e. the charge carried) then:

$$I(t) = q \sum_{k=-\infty}^{\infty} \delta(t - t_k) \tag{3}$$

the mean current flowing is obtained by taking an average over time of $I(t)$, such that:

$$\langle I \rangle = \frac{1}{T} Lim_{T\to\infty} \int_{t=0}^{T} I(t)dt \tag{4}$$

This evaluates as:

$$\langle I \rangle = qF \tag{5}$$

where $F = M/T$ is the mean arrival rate of the source quanta. The autocorrelation function of the current is:

$$\langle I(t)I(t+\tau) \rangle = q^2 F \delta(\tau) + q^2 F^2 \tag{6}$$

where the first term on the RHS arises because all the current pulses due to photon arrivals are uncorrelated, while the second term is the mean square value of the time averaged current. Taking the Fourier transform of the autocorrelation and realising this is the power spectrum of the process yields:

$$S_I(\nu) = q\langle I\rangle + \langle I\rangle^2\delta(\omega) \tag{7}$$

This is the power spectrum of the current, where the first term is the fluctuation component (independent of frequency), while the second term is the dc component which is ignored. The current variance, $\sigma_I^2 = \langle[I(t) - \langle I\rangle]^2\rangle$, is the integral over the band from $-B$ to B of the fluctuation component of the power spectrum, thus:

$$\sigma_I^2 = 2q\langle I\rangle B \tag{8}$$

Similarly, for a radiant power made up of F photons per second:

$$\langle P\rangle = h\nu F, \quad S_P(\nu) = (h\nu)^2 F, \quad \sigma_P^2 = 2h\nu\langle P\rangle B \tag{9}$$

It is therefore apparent that the randomness of the shot noise is contained in the randomness of the quanta emitted by the radiant power source. Thus the mean squared shot noise current can be given as:

$$\overline{i_{GR}^2}(\nu) = 2q\langle I\rangle B \tag{10}$$

where the shot noise is also often referred to as generation-recombination noise.

2.3 Excess Noise in Avalanche Photodiodes

Avalanche photodiodes, biased in avalanche mode, suffer from shot-noise connected with the unmultiplied signal, dark and background currents. The main noise source in the APD is itself the avalanche process that provides the gain in the device. The avalanche process is a probabilistic one, in that there are random fluctuations in the distance between successive ionising collisions. The nature of these variations is such that there are fluctuations in the number of secondary carriers generated per primary carrier injected into the gain region of the device. This fluctuation leads to an *excess noise* in the total signal current.

The electron/hole ionisation coefficient ratio, $k = \alpha_e/\alpha_h$, should be kept as large or as small as possible - in other words the avalanche process should be kept asymmetric. This is apparent when one considers the equations governing the excess noise factor in avalanche photodiodes. For electron injection into the high-field region we have:

$$F_e = M_e\{1 - (1 - k)[(M_e - 1)/M_e]^2\} \tag{11}$$

For hole injection, the excess noise factor for holes is given by:

$$F_h = M_h\{1 - (1 - (1/k))[(M_h - 1)/M_h]^2\} \tag{12}$$

The larger the ionisation coefficient ratio the smaller the excess noise factor, hence devices made from materials with larger ionisation coefficient ratios can be used at higher values of gain than can those made with materials having ionisation coefficients close to unity. The optimum gain for the APD is when its noise equals the noise from any attached receiver. To increase the gain further than this would make the APD noise dominate all other noise sources and would begin to reduce the signal to noise ratio of the receiver.

The gain-bandwidth product in an APD will also be greatest in devices made from materials whose ionisation coefficient ratio is maximised. In the case where the ionisation coefficient ratio, $k \rightarrow \infty$ the response time of the APD will be limited only by the time taken for a single transit across the depletion region, the worst case scenario is when the ionisation coefficient ratio, $k \rightarrow 1$, as the secondary carriers continuously recycle through the depletion region, introducing a long response time.

2.4 Noise Performance of Photodiodes

As discussed above, the noise current contributions due to Johnson noise and shot noise can be combined to estimate the total noise contribution present in the photodiode. If the r.m.s. (root mean square) optical power incident on a detector is $P_{inc}/\sqrt{2}$, then the r.m.s. photocurrent is given by:

$$i_{ph} = \frac{\eta q P_{inc}}{\sqrt{2} h\nu} \tag{13}$$

In addition to the signal on the detector, there is a nominal component due to background radiation, due to the ambient environment which leads to a background photocurrent, I_b. The other current source present in the device is due to thermally-generated electron-hole pairs in the depletion region, which is normally called the dark current, I_{dark}. All of these currents are generated randomly and thus give rise to a shot noise in the output, and we have seen that the equivalent mean squared shot noise current can be represented as:

$$\overline{i_s^2} = 2q(I_{ph} + I_b + I_{dark})B \tag{14}$$

where B is the bandwidth of the device.

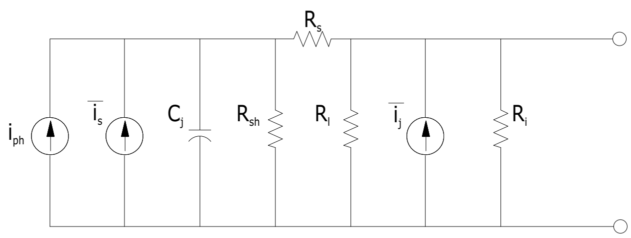

Figure 1: Noise equivalent circuit of a photodiode.

The Johnson or resistance noise at the output of the photodiode due to the various resistances in the diode circuit, as presented in Fig. 1, is given by the mean square Johnson noise current as:

$$\overline{i_J^2} = \frac{4k_BTB}{R_{eq}} \tag{15}$$

where R_{eq} consists of the contributions of the diode shunt resistance (R_{sh}), the series resistance (R_s) and the load resistance (R_l) and is given as:

$$R_{eq} = \left(\frac{1}{R_{sh}} + \frac{1}{R_l} + \frac{1}{R_i}\right)^{-1} \tag{16}$$

where R_i is the input resistance to a preamplifier following the detector and R_s is neglected because it is normally only a few ohms in series.

The signal-to-noise ratio of the photodiode can thus be calculated from the signal power, given by $i_{ph}^2 R_{eq}$, and the total noise power at the output, given by

$[i_s^2 + i_J^2]R_{eq}$. This leads to:

$$\left(\frac{S}{N}\right)_{power} = \frac{\frac{1}{2}\left(\frac{\eta q P_{inc}}{h\nu}\right)^2}{2q(I_{ph} + I_b + I_{dark})B + \frac{4k_B TB}{R_{eq}}} \tag{17}$$

2.4.1 Noise Equivalent Power

One measure of the sensitivity of a photodiode is the noise equivalent power or NEP, which occurs when the photocurrent equals the noise current thus making the signal-to-noise ratio unity. The NEP is calculated for a bandwidth of 1 Hz. From Eq. 17, for $(S/N) = 1$ we have:

$$\frac{\eta q P_{inc}}{\sqrt{2}h\nu} = \sqrt{\overline{i_N^2}} = \left[2q(I_{ph} + I_b + I_{dark}) + \frac{4k_B T}{R_{eq}}\right]^{1/2} B^{1/2} \tag{18}$$

where $\overline{i_N^2} = \overline{i_s^2} + \overline{i_J^2}$ and the NEP is thus given as:

$$NEP = \frac{h\nu}{\eta q}\left[2q(I_{ph} + I_b + I_{dark}) + \frac{4k_B T}{R_{eq}}\right]^{1/2} \tag{19}$$

The NEP is thus the minimum detectable power. It is important to note that the avalanche gain of an APD can increase the signal-to-noise ratio and hence can substantially reduce the NEP compared to photodiodes without gain.

3 Summary

This module has examined the noise sources of a photodiode. Johnson noise and shot noise, noise sources which are present in all photodiodes, have been explained and quantified. Excess noise, which is noise only present in avalanche photodiodes, has also been described. Finally, the module has presented a noise equivalent circuit model and described noise equivalent power, the minimum detectable power of a photodiode.

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