NEP – Noise Equivalent Power

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Noise is an important specification when one chooses a detector for any measurement problem. There are a lot of different definitions for noise; one possible way to quantize noise is the so-called Noise Equivalent Power (NEP). This paper covers the definition of NEP, how it is measured, and which parameters have an impact on this value. The focus is set on its practical use and includes some examples, such as how to calculate the minimum detectable power from the noise specification.

NEP Definition

Photodetector sensitivity is a convenient, even necessary, metric by which the performance of a particular photodetector can be quantified and compared with other detectors. However, it can be difficult to define and verify. The Noise Equivalent Power (NEP) is the common metric that quantifies a photodetector's sensitivity or the power generated by a noise source. But even this common metric can cause confusion given the different definitions and calculation methods used to describe it [1]. The most commonly used definition for NEP is the following: The input signal power that results in a signal-to-noise ratio (S/R) of 1 in a 1 Hz output bandwidth [2]. For detectors, such as photodetectors, the NEP expresses the sensitivity of the device and is given in Watts per square root of Hertz (W/√Hz).

Essentially, the NEP expresses the minimum detectable power per square root bandwidth of a given detector; in other words, it's a measure of the weakest optical signal that can be detected. Therefore, it is desirable to have an NEP as low as possible, since a low NEP value corresponds to a lower noise floor and therefore a more sensitive detector. Even at higher input intensities, a low NEP is beneficial since it will lead to lower noise characteristics in the output signal.

Even when blocking the optical input to a photodetector, there will be some amount of generated output noise (such as thermal or shot noise) that results in a certain average output noise power into the connected load. This noise power and thus the resulting noise-equivalent power, both depend on the related measurement bandwidth. This bandwidth is typically normalized to 1 Hz, which is usually far below the detection bandwidth, to allow detectors with different bandwidth specifications to be directly compared.

Specifically, Thorlabs uses NEP to refer to the optical power incident upon a photodetector system. In this case, the NEP is known as the "optical NEP" [1]. Alternatively, the NEP can refer to the signal power portion that is absorbed by the detector (the power at the output of the detector). This can come from various sources such as Johnson or shot noise and is called "electrical NEP" [1].The optical NEP is equal to the ratio of the electrical NEP and the optical coupling efficiency of the detector system.

In specifications, Thorlabs assumes a coupling efficiency of 1 and does not distinguish between electrical and optical NEP.

The Noise Equivalent Power depends on the optical wavelength as well, since the responsivity of the detector is wavelength dependent. For a given detector, the lowest NEP is achieved at the wavelength with maximum detector responsivity. In Thorlabs' specifications, this value is stated as "Minimum NEP." To

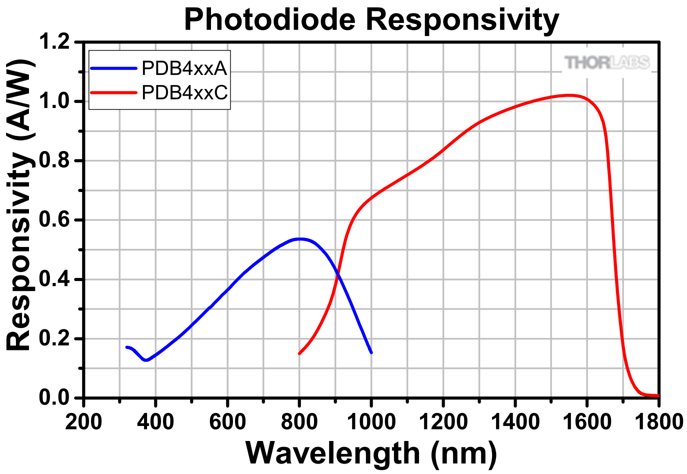

Figure 1: PDB4xxA and PDB4xxC detector responsivity

calculate the NEP at a different wavelength λ, the following formula can be used:

$$NEP(\lambda) = NEP_{min} \times \frac{R_{max}}{R(\lambda)}. \qquad (1)$$

Here, NEP_{min} is the NEP as given in the specifications, R_{max} is the maximum responsivity of the detector, and $R(\lambda)$ is the responsivity of the detector at wavelength λ. R_{max} and R(λ) can be read from the detector responsivity curves that are provided in the Operating Manual. Figure 1 shows a typical example.

When comparing detectors of the same model but for different wavelength ranges (e.g., Thorlabs' PDB410A and PDB410C photodetectors), their NEP is remarkably different, although their electrical amplifiers are identical. This NEP difference is mainly caused by different maximum detector responsivities.

While the spectral density of the detector's output noise is caused by different sources, the electronic noise from the electrical amplifier is the dominate component. Transimpedance amplifiers, which are predominantly used in detectors, exhibit a frequency-dependent NEP that increases with frequency until the 3 dB cut-off frequency is reached. For this reason, the Minimum NEP value given in specifications is only valid for the specified NEP frequency range.

Note: In this paper, the NEP will often be given for a specified bandwidth.

When comparing NEP values between different detector models and manufacturers, it is important to pay attention to the NEP's specified bandwidth, keeping in mind that this bandwidth typically differs from the detector's bandwidth or frequency response. Figure 2 shows a typical spectral density noise curve for the PDB460C photodetector, measured using an electrical spectrum analyzer with a resolution bandwidth of 100 kHz.

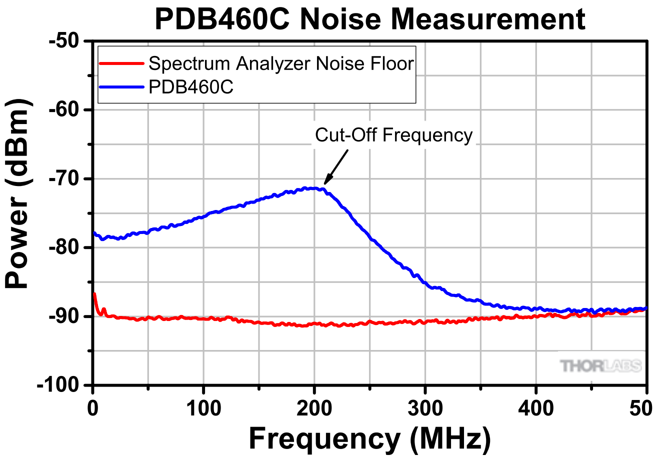

Figure 2: PDB460C RF Output Spectral Noise

Minimum Detectable Optical Power

The NEP of a detector is the optical power incident to the detector that needs to be applied to equal the noise power from all sources in the detector; in other words, NEP is the optical power that results in an SNR of 1 [2]. Basically, this represents the threshold above which a signal can be detected. The minimum detectable power P_{min} can be easily calculated using the following formula:

$$P_{min} = NEP(\lambda) \times \sqrt{BW}. \qquad (2)$$

Here *NEP(λ)* is the wavelength-dependent NEP and *BW* is the measurement bandwidth.

Limiting the measurement bandwidth using additional electronic bandpass filters significantly reduces the amount of noise in the measurement and hence the minimum detectable optical power. Without any output filtering, the photodetector's bandwidth or frequency response is a good approximation of measurement bandwidth.

It should be noted, however, that the listed NEP value is only valid for the specified frequency range. The measurement bandwidth must be less than or equal to that frequency range for the above calculation to be valid. If the measurement bandwidth exceeds that range, the NEP needs to be adjusted. However, this will increase the NEP significantly and oftentimes manufacturers will not provide the necessary information to make this. The next section outlines the procedure for generalizing the NEP response.

Using advanced methods such as lock-in detection, it is possible to detect much weaker signals, provided that these have a bandwidth far below the detector bandwidth. In effect, the detection bandwidth is limited to a value far below 1 Hz in order to reduce the noise power. This approach requires a correspondingly longer averaging time. From the Nyquist theorem, the required averaging time t_{avg} can be calculated as:

$$t_{avg} = {}^{1}\!/_{(2 \times BW)} \qquad (3)$$

Example

The NEP of the Thorlabs' PDB460C balanced detector is specified as 6 pW/√Hz within an NEP frequency range from DC to 100 MHz. It can detect a signal power of 6 pW with a signal-to-noise ratio (SNR) of 1 after 0.5 seconds averaging time within a 1 Hz bandwidth.

The NEP decreases inversely to the square root of the averaging time. So, if the averaging time is extended to 50 sec, the NEP, for this example case, can be reduced by a factor of 10.

Using the same detector with measurement bandwidth limited to DC - 100 MHz using external filters, the minimum detectable optical power is 60 nW. Calculating the minimum detectable power for the full specified detector bandwidth from DC – 200 MHz, the value increases to 85 nW. However, this calculation does not take into account the increase of the NEP for frequencies beyond those specified within the NEP frequency range. Therefore, Thorlabs additionally specifies the parameter Integrated Noise from DC to the cut-off frequency, referred to the input. This parameter is identical to the minimum detectable optical power under the condition that the measurement bandwidth is equal to the detector bandwidth. For the PDB460C detector, the integrated noise from DC – 200 MHz is 130 nW.

Estimating the NEP of a Specific Photodetector

As mentioned earlier, sometimes it might be advantageous to know the exact shape of the NEP frequency dependency rather than the single value specified by most manufacturers. This section explains in detail how to calculate the NEP curve from a single measurement of the output noise spectral density.

In order to extrapolate the NEP frequency dependency curve, the NEP must be calculated in steps, starting with the minimum frequency band (typically given in the detector's specifications). In each step, the NEP is calculated for a frequency range and the results are built up to provide an expanded NEP curve. Figure 3 shows an expanded NEP graph for Thorlabs' PDB460C photodiode.

The output noise spectral density can be measured either by an electrical spectrum analyzer or by sampling the detector's output signal with a fast Analog-to-Digital Converter (ADC), followed by an Fast Fourier Transformation (FFT) to calculate the power density spectrum of the sampled signal. For detectors with a high bandwidth, an electrical spectrum analyzer is preferred due to the limited sampling rate of commercially available ADC cards.

It is important to measure the output noise density without incident light (i.e., the optical input must be completely darkened). For most detectors, the recorded spectrum is close to the resolution limit so the intrinsic noise floor of the measurement device (the spectrum analyzer) must be taken into account. Therefore, a second measurement is necessary with switched off detector or terminated analyzer input in order to determine the measurement noise floor.

Procedure

1. Execute the output noise spectral density measurements as described above over the entire frequency range of interest.
2. Correct the measured power density spectrum by subtracting the spectrum analyser's noise floor. Please note that usually the recorded output values are measured in dBm; convert them into linear values (e.g. Watts) first.
3. Normalize the measured values to a 1 Hz bandwidth by dividing them by the resolution bandwidth of the spectrum analyzer. Depending on the frequency range, the resolution bandwidth should be selected as small as possible for a reasonable sweep time.
4. Multiply the normalized power with the frequency difference between two adjacent measurement points to calculate the integral power between the two measurement points.
5. Sum up the calculated integral power per frequency step up to the first desired "measurement bandwidth." The calculated value represents an integrated output noise power, with units of Watts [W].
6. In order to get the NEP, the calculated integrated output noise power needs to be calculated back to the corresponding optical input power. Therefore, the integrated output noise power $P_{out,NI}$ [W] is converted into an integrated output noise voltage $U_{out,NI}$ [V] into the output load R_L [Ω]:

$$U_{out,NI} = \sqrt{P_{out,NI} \times R_L} \quad . \qquad (4)$$

Note that the output load is the input impedance of the spectrum analyzer, which is typically 50 Ω.

Then, this output noise voltage $U_{out,NI}$ [V] is divided by the transimpedance gain G [V/A], which results in the integrated input noise current $I_{in,NI}$ [A]:

$$I_{in,NI} = {}^{U_{out,NI}}\!/_{G} \quad . \qquad (5)$$

Please note that the transimpedance gain can be specified either for "High-Z" (high impedance) or 50 Ω termination. In general, electrical spectrum analyzers have a 50 Ω input, and hence, the transimpedance gain for 50 Ω should be applied.

7. Divide the integrated input noise current $I_{in,NI}$ [A] by the maximum detector responsivity $\mathfrak{R}_{max}$ [A/W], as the NEP is defined for the maximum responsivity. The result is the integrated input noise power [W]:

$$P_{in,NI} = {}^{I_{in,NI}}\!/_{\mathfrak{R}_{max}} \quad . \qquad (6)$$

8. As the final step, the integrated input noise power is divided by the square root of the frequency bandwidth that was used for integration. This operation normalizes the integrated input noise to a 1 Hz bandwidth, and the measurement unit is W/√Hz.

$$NEP = {}^{P_{in,NI}}\!/_{\sqrt{BW}} \qquad (7)$$

9. Repeat steps 4 through 8 with the next limit frequency until the limit frequency reaches the range of interest.
10. Combine all calculated NEP values to the desired frequency-dependant NEP curve. Figure 3 shows a typical example for Thorlabs' PDB460C detector.

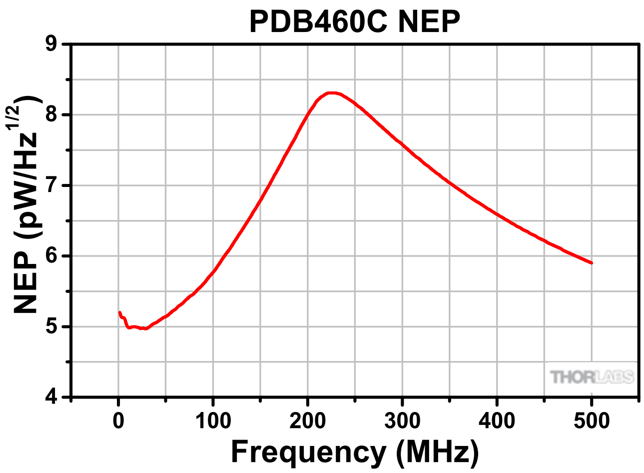

Figure 3: PDB460C Measurement Bandwidth Dependent NEP

For the specified NEP measurement bandwidth from DC to 100 MHz, the NEP is 6 pW/√Hz. For the full detector bandwidth (DC to 200 MHz in this specific case), the NEP is increased to ~ 8 pW/√Hz. Using this NEP value the calculated minimum detectable power is 113 nW, which is consistent with the detector Integrated Noise (130 nW) specified for this product. The small difference is caused by a conservative specification of the Integrated Noise to consider device variations.

Related Parameters and Conversions

NEP is equal to the noise spectral density, expressed in units of A/√Hz or V/√Hz, divided by the detector responsivity expressed in units of A/W or V/W, respectively.

The possible signal-to-noise (SNR) ratio of a measurement (for a bandwidth of 1 Hz) can be estimated simply as the available input power divided by the noise equivalent power NEP.

The Specific Detectivity *(D*)* is derived from the NEP with relation to the active detector area A:

$$D^* = {\sqrt{A}}/{NEP} \left[\frac{cm\sqrt{Hz}}{W}\right] \tag{8}$$

The Specific Detectivity, *D** is used in cases when the noise scales as the square root of the area, such as shot noise. The advantage of using specific detectivity *D** is that it allows for the comparison of detectors that have different active areas. Some sources state a different formula for the Specific Detectivity, where the square root of the measurement bandwidth, *dF*, appears, as shown here:

$$D^* = {\sqrt{A \times dF}}/{NEP} \quad . \tag{9}$$

However, this definition refers to a different NEP definition that is not normalized to the measurement bandwidth, measured in W; though, both definitions lead to the same result and measurement unit.

Thorlabs specifies the Integrated Noise (in units of watts [W]) for many detectors. It refers to the optical input power and is always given for the detector bandwidth. This value represents the minimum detectable optical power without any additional output filtering assuming an SNR of 1.

The Overall Output Noise Voltage [V_{RMS}] is the value that can be measured across a 50 Ω load at large bandwidth (e.g., if the RF output is connected to a 50 Ω terminated scope input).

Selecting the Optimal Photodetector

To select the optimal photodetector for a certain application, a number of different factors need to be considered. The wavelength range, the detector bandwidth, the conversion gain, and the detector size should match the requirements of the intended measurement.

For a noise optimized measurement, the following hints might be helpful to select the appropriate detector:

- Select a detector with a high responsivity at the wavelength of interest. The responsivity directly affects the resulting NEP value.
- Select the detector with the smallest possible active area of the photodiode. The choice of a detector with a large active area is not advantageous with respect to the NEP for two reasons:
  - For the majority of photodetectors, the generated noise is proportional to the square root of the detector size.
  - Large active areas reduce the achievable gain bandwidth product of the photodetector and hence the transimpedance gain in the first amplifier stage for a given bandwidth or frequency response. Lower transimpedance gain in the first amplifier stage increases the electronic noise, which is the dominant component for most photodetectors, thereby leadint to an increased NEP value.
- Select the photodetector with the smallest possible bandwidth (frequency response). The assumption that "unused" bandwidth can be eliminated using additional electronic lowpass filters is only partially correct. Due to the fact that the gain bandwidth product of the transimpedance amplifier is constant, a wider bandwidth requires a lower transimpedance gain. Again, this leads to an increased electronic noise and hence an increased NEP.
- Select an APD-based (Avalanche-Photodiode-based) detector for low-light-level applications requiring an extremely low NEP. Thanks to the optical multiplication process, expressed by the M Factor

(M), the achievable NEP decreases approximately by 1/M.

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[1] Samuel Leclercq, “Discussion about Noise Equivalent Power and its use for photon noise calculation” (web: http://www.iram.fr/~leclercq/Reports/About_NEP_photon_noise.pdf)

[2] P.L. Richards, "Bolometers for infrared and millimeter waves," Journal of Applied Physics **76**, 1 (1994)