BROADCOM®

Application Note

AFBR-S4Pxx

Broadcom NIR SiPMs

Introduction

The Broadcom® AFBR-S4Pxx products are a silicon photomultiplier (SiPM) series that is used for ultra-sensitive precision measurements of single photons in the red and near infrared (NIR).

The Broadcom NIR SiPM series provides optimized electro-optical performance parameters with best in-class performance in a wide range of applications, such as LiDAR, dTOF, and life sciences (flow cytometry, microscopy, fluorescence/ luminescence detection), and many more.

With two distinct NIR technologies, NIR30 and NIR20 Fast, Broadcom provides a NIR technology that is best suited for the application-specific needs of your system.

NIR30: The Broadcom NIR30 technology provides best-in class photon detection efficiency (PDE) and an ultra-wide dynamic range for applications where pulse durations are comparably long (several hundreds of nanoseconds up to continuous-wave scenarios). So it is a perfect SiPM for medical and life-science applications, such as the following:

- Flow cytometry
- (Two-photon) scanning microscopy
- Fluorescence detection systems
- Functional near-infrared spectroscopy (fNIRS)

NIR20 Fast: The Broadcom NIR20 Fast technology is a fast-timing optimized NIR SiPM. It features fast PDE response, very low noise characteristics (primary and correlated), and an ultra-wide dynamic range. So it is a perfect fit for applications where accurate timestamping is key, such as the following:

- Light detection and ranging (LiDAR)
- Direct time-of-flight (dTOF)
- Fluorescence lifetime imaging (FLIM)
- Long-distance optical communication links

Both technologies feature a 12.5-µm SPAD pitch that fits 6216 SPADs on a mm^2.

Both technologies are available in the same package type with an identical mechanical outline and active area, allowing for evaluation and comparison between the two technologies to find the best fit for your needs.

The SiPMs with 1 × 1 mm^2 come in a lead-frame package and provide a two-channel configuration. That is, the Si die is a 2×1 monolithic array with an active area channel size of 0.5 × 1 mm^2. This design allows an optimized fill factor with no gap between the two channels. The signal of the two channels can be read out by individual cathode pads on the package or shorted together to obtain a single-channel SiPM with a 1 × 1 mm^2 active area.

The following are the respective part numbers:

- AFBR-S4P11P012R (NIR30)
- AFBR-S4P0102L3R (NIR20 Fast)

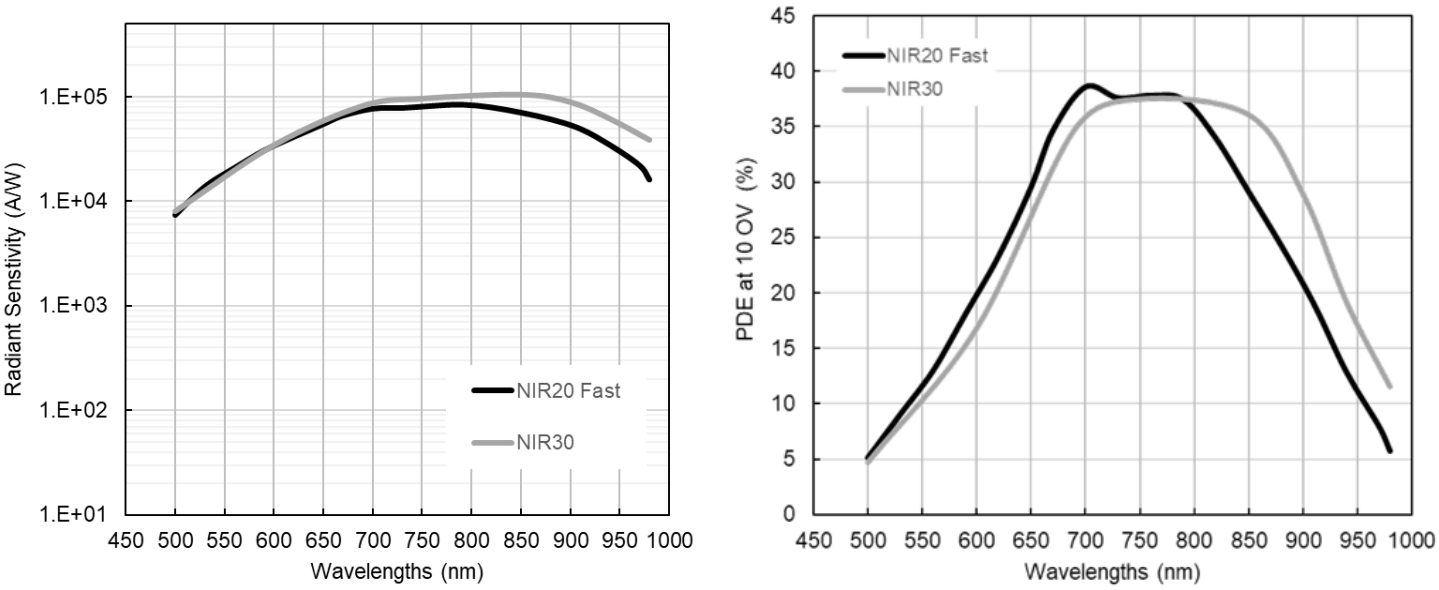
Advantages of the Broadcom NIR SiPMs

Silicon photomultipliers are solid-state photodetectors and provide single-photon detection capabilities. They are applied in numerous applications where dim light signals must be detected. As such, a key metric is the efficiency of the SiPM.

Broadom NIR SiPM technologies provide optimized performance with high efficiency for red and NIR light. An often used metric to compare efficiency is the radiant sensitivity (Figure 1). The radiant sensitivity, however, includes the gain of the detector. Consequently, high radiant sensitivity is not a good measure to compare the efficiency of detectors with a gain greater than 1.

For SiPMs, efficiency is expressed in terms of the photon detection efficiency (PDE). The PDE represents the effective efficiency of the SiPM (it includes the quantum efficiency, avalanche trigger probability, and geometric fill factor) and is to be compared to the quantum efficiency (QE) of a photomultiplier tube (PMT).

Figure 1: Radiant Sensitivity and PDE



However, optical detection systems are a complex interaction between many components. As such, well-balanced parameters that result in leading-edge performance are required.

Compared to other low-light detectors, such as avalanche photodiodes (APDs) or photomultiplier tubes (PMTs), Broadcom silicon photomultipliers offer further unique advantages.

Key Advantages over APDs

- **Single photon detectability**, due to its high intrinsic gain of $\times 10^5$ to $\times 10^6$.
- **Single photon timestamping capability**, due to the single photon detection capability and pulse rise times of only a few hundred of picoseconds.
- **Very low excess noise factor (ENF)**, due to the Geiger-mode operation in which the full charge stored in a microcell is released by a photon detection. This very well-defined charge content per microcell results in an unambiguous SiPM pulse response per photon.

  Example: The ENF of the Broadcom NIR20 Fast technology is less than 1.05 independent of the applied overvoltage.

Key Advantages over PMTs

- **Very low excess noise factor (ENF)**, as described in the preceding bullet.
- **High dynamic range at a single overvoltage setting.** Broadcom NIR SiPM technologies detect single photons or a very high photon flux at one overvoltage, and therefore, one gain setting. Changing the overvoltage depending on the light intensity is not required.

  With a SPAD pitch of only 12.5 µm and a recharge time of 15 ns, Broadcom NIR SiPMs can detect up to 10^{11} photons/(sec · mm^2) before saturating.

  At a wavelength of 900 nm:
  - And a CW light source, over 10^9 photons/(sec · mm^2) can be detected.
  - And a pulsed light source (pulse width of 10 µs), almost 10^5 photons/(sec · mm^2) can be detected with less than a 1% deviation from linearity.
- **SiPMs are not damaged when exposed to bright light.**

Furthermore, the low operation voltage of below 60V across the full temperature range reduces regulatory requirements and simplifies the electronics design for the SiPM voltage supplies and readout systems.

The following table summarizes the advantages of SiPMs compared to APDs and PMTs.

Table 1: Comparison of Low-Light Detection Technology

Comparison of Low-Light Sensors	PMT Photomultiplier Tube	APD Avalanche Photodiode	SiPM Silicon Photomultiplier
Quantum Efficiency	25% ... 40%	60% ... 80%	... 80% (PDE: ... 65%)
Single Photon Detectability	√	—	√
Single Photon Time Resolution	√	—	√
Excess Noise Factor	Good	Poor	Good
Operation Voltage	1 kV ... 3 kV	100V ... 500V	20V ... 60V
Gain	10^4 ... 10^9	30 ... 300	10^5 ... 10^7
Robustness	—	√	√
Insensitivity to Magnetic Fields	—	√	√
No Damage in Bright Light	—	√	√
Miniaturization	—	√	√
Low Pitch Tileability	Poor	Good	Good

Electro-Optical Performance

Optical detection system requirements are often a complex interaction of many parameters. With two distinct NIR SiPM technologies, Broadcom provides unprecedented performance in dim light detection.

Figure 2 to Figure 5 show a comparison of the electro-optical parameters between the NIR30 and NIR20 Fast technologies. The grey data represents the NIR30 technology, whereas the NIR20 Fast technologies is drawn in black.

Figure 2: PDE Spectra

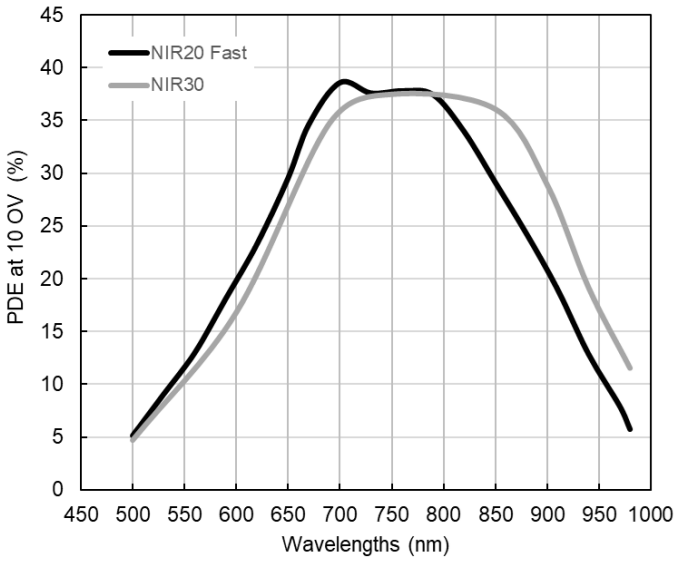


Figure 3: PDE vs. Overvoltage

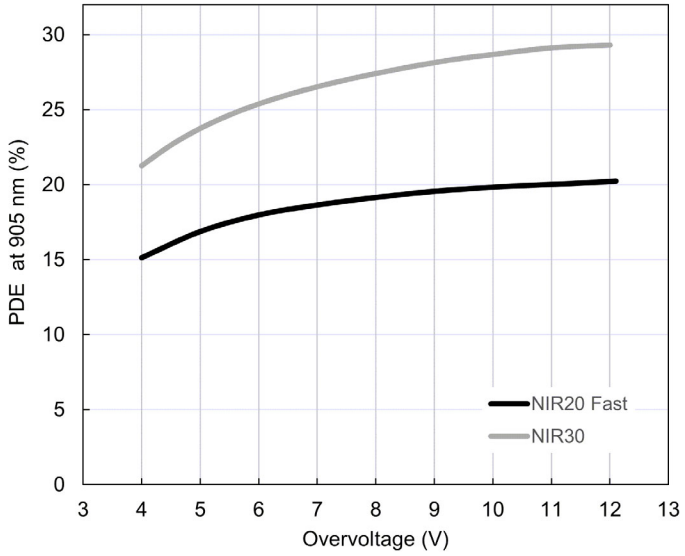


Figure 4: Primary Noise (DCR)

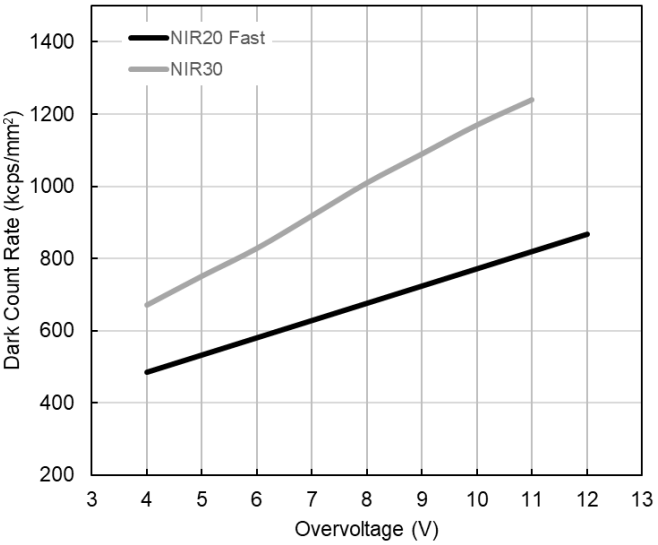
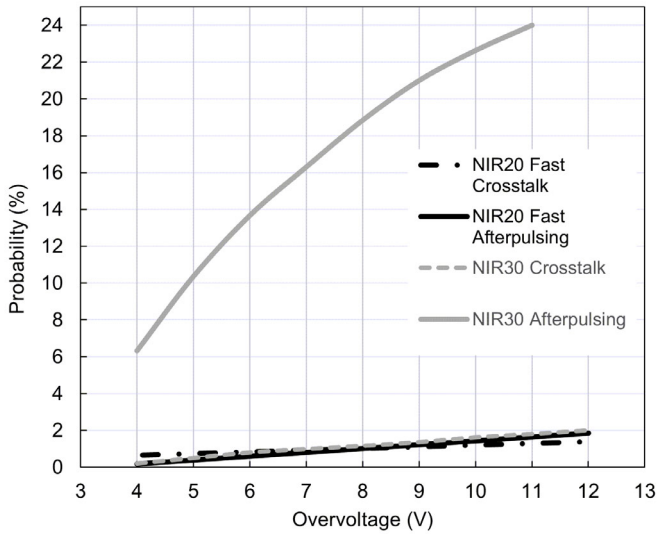


Figure 5: Correlated Noise (Crosstalk and Afterpulsing Probability)



As evident from Figure 2 to Figure 5, not only the right choice of detector technology but also the operation voltage determines the system performance.

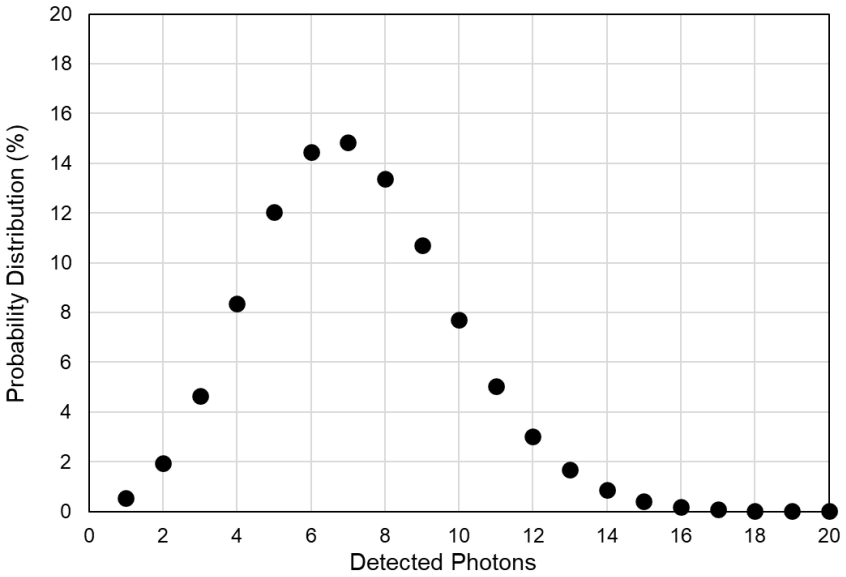
For example, operating a SiPM at a higher overvoltage can improve the signal-to-noise due to an increase of the PDE. At 905 nm, once a 10V overvoltage is reached, the PDE does not increase significantly anymore (Figure 3), while the dark count rate and correlated noise continue to increase linearly (Figure 4 and Figure 5). As a consequence, the SNR may deteriorate for overvoltages higher than 10V.

In this context, it is particularly important to use the correct metric and parameter definition. In the preceding example, it is assumed that the dark count rate is the main contributor to the SNR. This is the case for long light pulse/integration windows.

On the other hand, there are measurement scenarios where the dark count rate has only a negligible contribution to the SNR. An example is a system that requires the determination of the photon content of pulses with a pulse width of 400 ns. The total integration window is chosen to be 500 ns, which also includes the charge for the signal falling edge determined as 5 times the SiPM recharge time constant (75 ns).

To demonstrate, Poissonian statistics can be used to calculate the probability for the occurrence of a concrete number of dark counts per time interval (here 500 ns). Figure 6 shows that for both Broadcom NIR technologies, in most of the 500-ns time windows, there will be no dark count detected. In about 30%, there will be one, and in less than 10% of events, there will be two dark counts within the 500-ns integration window.

Figure 6: Probability Distribution of Dark Counts per 500-ns Window



In this measurement scenario, the SNR is dominated by the statistics of photon detection rather than the dark noise contribution. In Figure 7 the noise is plotted as function of the number of detected photons. For as little as 5 detected photons, the noise exceeds a value of two photons, thus being larger than the contribution of dark counts.

Figure 8 plots the probability distribution for the number of photons detected from 20 incoming photons with a wavelength of 700 nm and detected by the AFBR-S4P0102L3R (NIR20 Fast). As seen by the width of the distribution, the noise given by the physics of photon detection has a larger contribution to the SNR than dark counts have in a 500-ns window.

Similar to the preceding example, the SNR can be estimated depending on the measurement scenario. Each scenario is unique and might need to include additional noise contributions such as crosstalk or afterpulsing.

Figure 7: Noise vs. Detected Photons

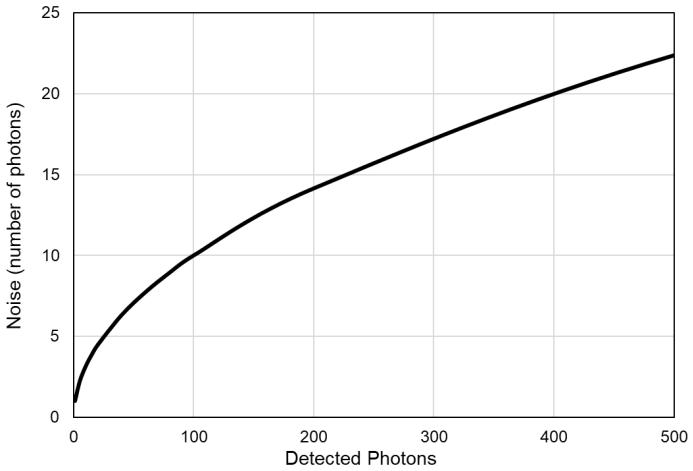
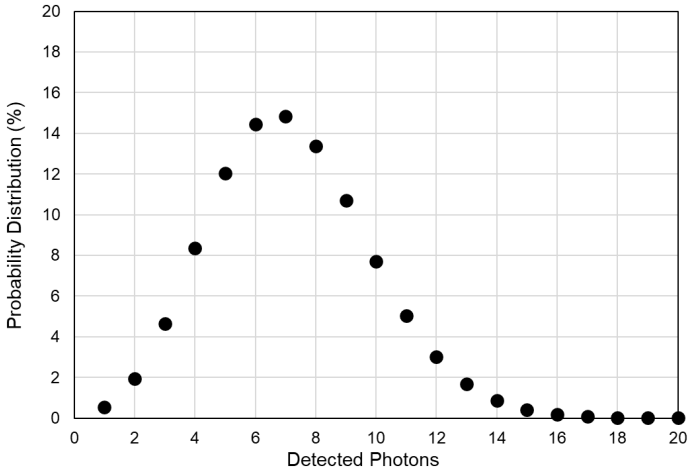


Figure 8: Probability Distribution (Detected Photons, 700 nm)



Basic Electrical Model

A simplified SiPM electrical model can be used to simulate the 1-p.e. (photo-electron) pulse of an SiPM. The following are the main components of such a model:

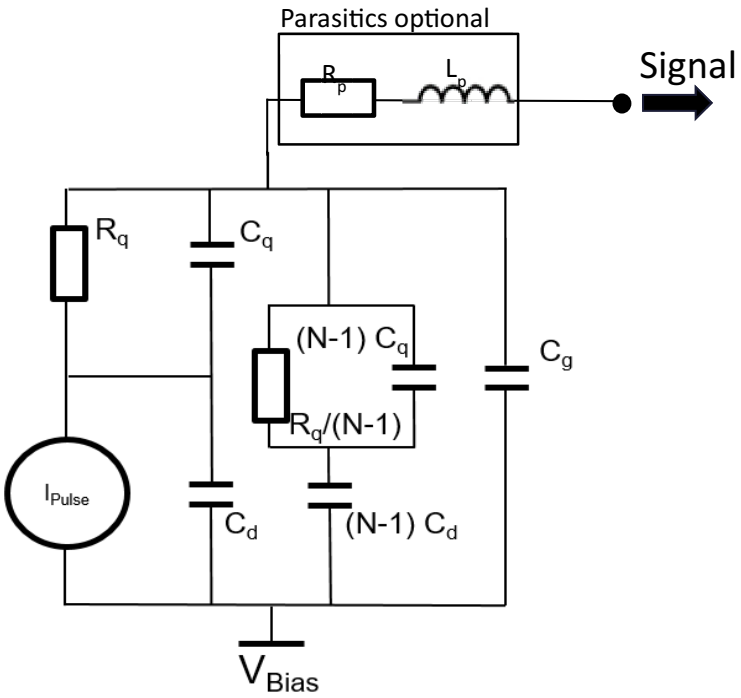
- **A current source** that mimics the avalanche in the microcell and the subsequent current pulse.
- **The firing microcell**
  A SiPM microcell consists of a single photon avalanche diode (SPAD) and a quenching resistor. The SPAD is described by a capacitor with a capacity C_d. The quenching resistor is modeled with the resistive component R_q and the parasitic capacity C_d.
- **The inactive microcells**
  The inactive cells are modeled similar to the active cells. The value of C_d, R_q, and C_q are scaled accordingly for N microcells in parallel.
- **The parasitic capacitance of the grid**
  An SiPM is an array of N microcells. The grid that interconnects the individual microcells introduces parasitic capacitances to the SiPM. Therefore, SiPMs with larger active areas typically have a larger Cg value. The grid capacitance, together with a load resistor from a low-pass filter to the readout line of the SiPM, can limit the signal bandwidth.
- **(Optional) Parasitics of the SiPM and package** such as the series resistance and series inductance.

Table 2 lists the individual values measured on a 1 × 1 mm^2 for both technologies, NIR30 and NIR20 Fast. Figure 9 depicts the underlying model (adapted from F. Corsi et al, Modelling a silicon photomultiplier (SiPM) as a signal source for optimum front-end design, NIM A 572 1 pp. 416-418, 2007). The induced current into the model by the current source depends on the exact pulse properties. Ideally a very short (duration < 1 ps) rectangular pulse (infinite steep rising/falling edge) is used. The pulse amplitude can be calculated form the stored charge in the microcell at a given overvoltage and the pulse duration.

Table 2: Electrical Parameters

Symbol	NIR30 AFBR-S4P11P012R	NIR20 Fast AFBR-S4P0102L3R	Unit
C_d	4	4	fF
dV	10	10	V
R_q	2.2	2.1	MΩ
C_q	1	1	fF
N	6216	6216	—
C_g	14.5	14.5	pF
Optional			
R_p	2	2	Ω
L_p	5	5	nH

Figure 9: Basic SiPM Electrical Model



Depending on the readout, further parasitics may be included (capacitance, inductance).

Bandwidth limitations of the readout electronics can be approximated by a low-pass filter in the readout line.

The parameters of the current pulse can be calculated by the charge stored in the diode at the applied overvoltage such that the integral of the current pulse corresponds to the charge on the SPAD. For a 10V OV, the following parameters can be used:

- T_{rise} = 5 ps
- T_{fall} = 5 ps
- T_{on} = 15 ps
- Pulse amplitude: 2 mA

NOTE: Customers must validate the model with their own setup/application.

Pulse Shape

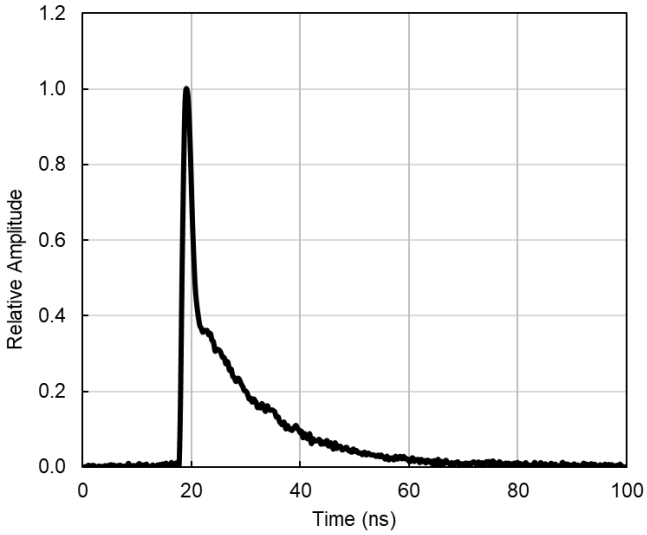
The exact output pulse shape of the SiPM depends not only on the SiPM parameters, but also on the pulse shape of the illumination. Generally, the output pulse is a convolution of the SiPM intrinsic pulse and the light source's pulse shape.

The intrinsic SiPM pulse (single photon response) of the NIR30 and NIR20 Fast technology is almost identical.

Figure 10 shows a pulse acquired on the AFBR-S4P0102L3R (1 × 1mm^2 configuration). The pulse was acquired with the SiPM biased at a 10V overvoltage using a laser with a pulse width less than 100 ps and without an amplifier or shaping circuit. Hence, the pulse shows the intrinsic SiPM pulse shape at full bandwidth.

The two typical SiPM pulse components can clearly be distinguished. The fast pulse component originates by the parasitic capacitance of the quenching resistor and has a typical width of a few nanoseconds. The recharge component is caused by the recharge of the SPAD capacitance via the quenching resistor. The shape follows an exponential behavior with a time constant (recharge time constant τ) given by the inverse product of $R_q \times C_d$.

Figure 10: Typical SiPM Pulse Shape



Bandwidth limitations or signal shaping might lead to different pulse shapes. Also, if the illuminating pulse width is longer than approximately 1 ns and/or the intensity is high, the pulse shape can deviate from the one shown.

Evaluation Options

Two dedicated evaluation kits are available for evaluation of Broadcom NIR SiPM technologies:

- AFBR-S4EP001 (NIR30 Evaluation Kit)
- AFBR-S4EP002 (NIR20 Fast Evaluation Kit)

AFBR-S4EP001 (NIR30 Evaluation Kit)

For detailed information, refer to the AFBR-S4EP001 application note (*AFBR-S4EP001 – NIR30 SiPM Evaluation Kit*).

The AFBR-S4EP001 is an SiPM evaluation kit designed for the NIR30 SiPM technology.

The evaluation kit includes the following components:

- One AFBR-S4P11P012R on a PCB
- An amplifier PCB with (Figure 12):
  - A DC-coupled output
  - Pole-zero cancellation filtered output for high count rate and timing measurements.
- A round DC readout PCB for high dynamic range measurements. The DC readout PCB includes a 50Ω load resistor (Figure 15).

Figure 11: Components of the AFBR-S4EP001

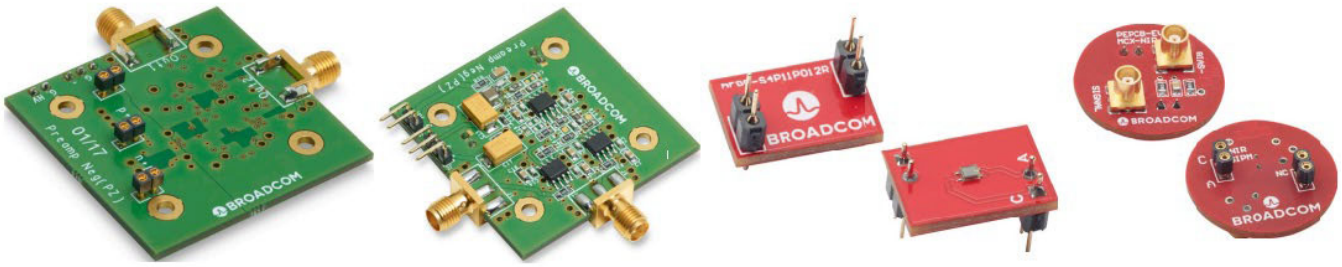
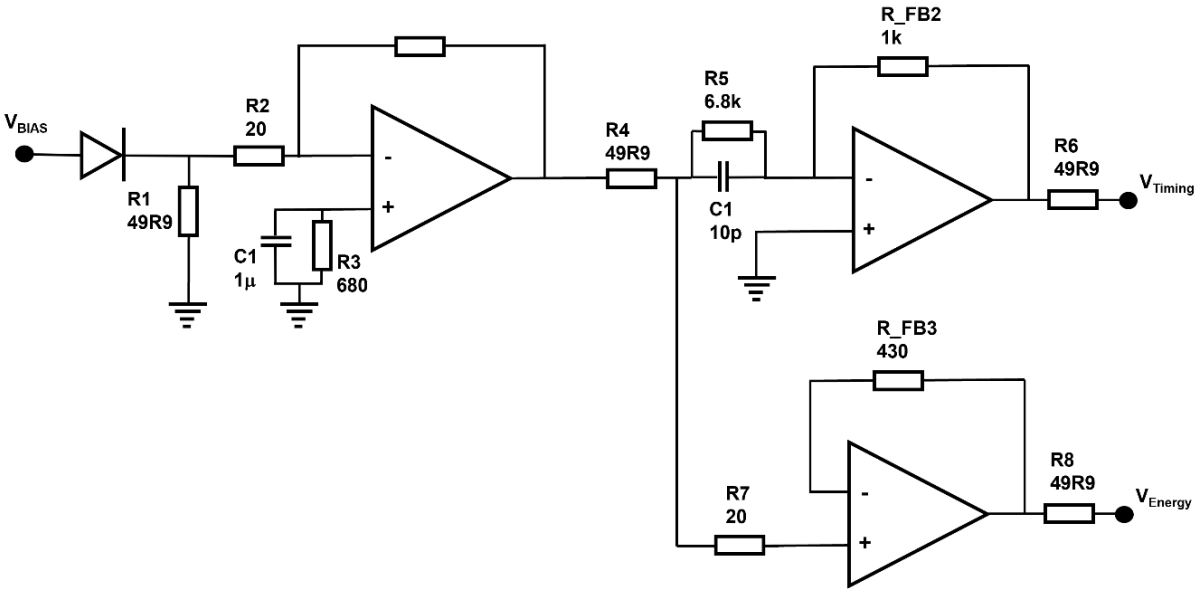


Figure 12: Basic Schematics of the NIR30 Evaluation Kit Amplifier Circuit



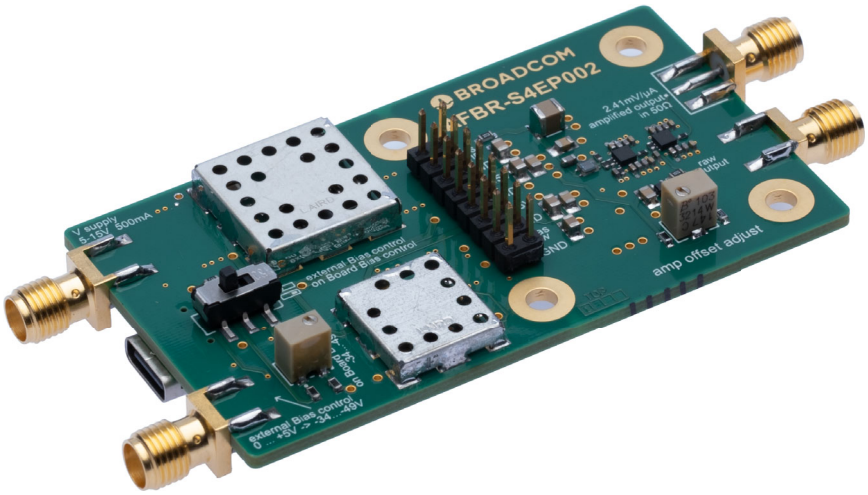
AFBR-S4EP002 (NIR20 Fast Evaluation Kit)

For detailed information, refer to the AFBR-S4EP002 application note (*AFBR-S4EP002 – NIR20 Fast SiPM Evaluation Kit*).

The Broadcom AFBR-S4EP002 is an evaluation kit specifically designed for the requirements and features of the NIR20 Fast technology.

The kit includes two AFBR-S4P0102L3R: one in the amplifier branch for optimized performance in low-light applications and one in the DC path without an amplifier to provide the highest dynamic range.

Figure 13: AFBR-S4EP002 Top Side with Amplifier Branch



Amplifier Branch

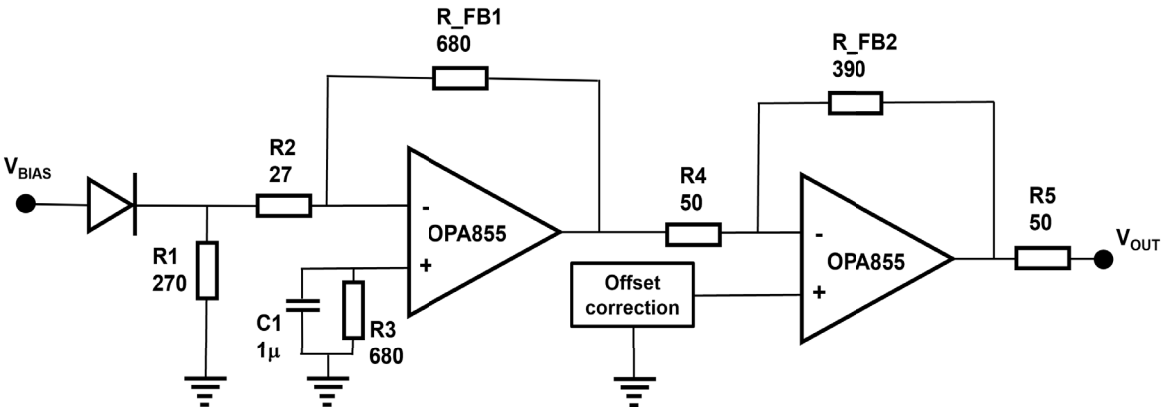
The evaluation kit provides all necessary features on-board including the following:

- The SiPM supply
- The SiPM (1×1 mm^2 active area)
- Analog amplifiers

It can be powered from a single USB C connector or by an external power supply connected via an SMA connector.

The SiPM overvoltage can be controlled and set via a potentiometer (internal) or via a control voltage SMA input (external).

Figure 14: Simplified Schematic of the Amplifier Circuit



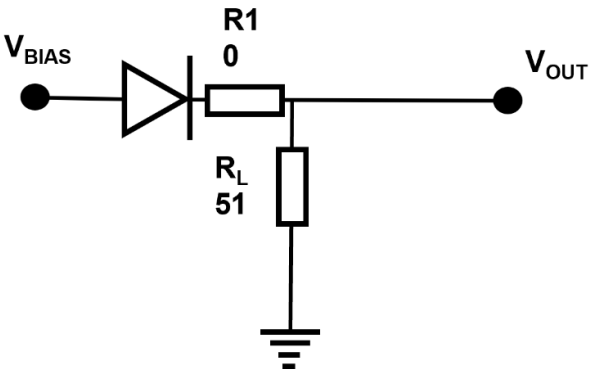
DC Branch

On the bottom side of the PCB, there is an AFBR-S4P0102L3R SiPM with the signal directly connected to an SMA output.

In the default setting, the SiPM signal is retrieved over a 50Ω load resistor, resulting in an effective 25Ω when coupled into an oscilloscope over 50Ω input impedance.

If 50Ω impedance matching is required, customers can add a 50Ω (R1) series resistor close the SiPM cathode using the solder pads.

Figure 15: Readout Schematics of the DC Branch



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