Amplification Technologies
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Application Notes: Discrete Amplification Photon Detector

General Description

The Discrete Amplification Photon Detector (DAPD) is delivered in a TO8 hermetically sealed package. The TO8 contains a two- or three-stage thermoelectric cooler (TEC), a thermistor for temperature control of the TEC and the DAPD photon detector. The DAPD is inserted into the DAPD Evaluation Module, type 2 (DEM2). An external pre-amplifier is used, where the connection between the DEM2 module and the amplifier is done using an SMA cable (>15GHz recommended, not supplied).

This document includes notes regarding:

1. DAPD in a TO8 Details
2. Operation and connection using the DEM2 and the external pre-amplifier
3. Explanation of the test procedures and the test sheet that is supplied with the product
4. Cooling and ESD consideration

1. DAPD Technology

The Discrete Amplification Photon Detector (DAPD) is a photon detector capable of detecting single to multiple photon level photon packets, with an output signal that is proportional to the number of photons. The DAPD design is based on many avalanche channels each integrated with a dedicated negative feedback element. We call these micro amplification-channel cells or micro-cells in short. When a photon is absorbed in the absorption layer it generates an electron-hole pair. In the InGaAs/InP compound semiconductor material case, the hole reaches the microcell because of the electric field that is designed to attract it, toward the avalanche region. The hole then triggers an avalanche, and simultaneously, as the charge generated by the avalanche is build up at the negative feedback region, the negative feedback mechanism reduces the bias, which causes the avalanche to stop. This dynamic electronic process is referred to as "quenching" the avalanche. The process generates a precise charge, with a gain of approximately 100,000 for every detected photon.

The number of microcells in a 200µm aperture DAPD is 349, which determines the dynamic range. The throughput, which is the number of photons per unit time that can be discerned, is determined by the recovery time of the microcell, which is approximately 100ns.

DAPD Operation Considerations

The DAPD 1500 Series has a broadband $In_{0.53}Ga_{0.47}As$ (lattice matched to *InP*) absorption region, which is combined with a broadband anti reflection coating, provides photon-level sensitivity between 950nm to 1650nm at the recommended (cooled) operating temperature of -50°C.

The DAPD 1060 Series has an *InGaAsP* (lattice matched to *InP*) absorption region with a bandgap cutoff wavelength of 1.2µm at room temperature. This version provides sensitivity between 950nm to 1150nm at the recommended cooled operating temperature of -50°C.

With either the 1500-series or the 1060- series product, the Single-Photon Detection Efficiency (PDE) is flat across the operating wavelength range. The benefit of the 1060-series version is that it is using a higher bandgap absorption semiconductor, hence reducing the probability for Dark Events, in comparison to the lower bandgap $In_{0.53}Ga_{0.47}As$. The benefit of the 1500-series version is that it is operating at the 1500nm to 1600nm wavelength range, which is preferable to 1064nm in terms of atmospheric transmission, as well as for human-eye safety, as this wavelength is approximately 100 times less damaging to the human eye.

Operating the DAPD in a photon-detection mode requires a calibrated laser source at the desired operating wavelength, e.g. 1064nm or 1550nm, which serves as the photon(s) source. When calibrating the photon source, it is important to takes into account the Poisson distribution nature of photons, as well as to calibrate at different average packet energy, e.g. 0.1 photon/pulse, 1 photon/pulse, 10 photons/pulse, 100 photons/pulse, and 1000 photons/pulse, to make sure the response of the DAPD is correlated well with the laser source. The single-photon detection efficiency (PDE) testing that is provided in the test-sheet is performed with a calibrated source attenuated to 0.5 photon/pulse (see the "Test-Sheet" section below).

2. Operating and Biasing of the DAPD Using the DEM2

The Device Evaluation Module type 2 (DEM2) is an enclosure that contains four SMA connectors: 2 connectors for the temperature control of the TO8 (thermo-electric cooler and feedback thermistor), a connector for DC bias and a connector for the RF signal-out. The printed circuit board inside the DEM2 is optimized for the DAPD signal extraction on a 50Ω system. All examples in this document refer to this 50Ω system as an oscilloscope, but the customer circuitry will act in an equivalent manner to the 50Ω oscilloscope.

It is assumed the customer acquired the following necessary equipment to operate and verify the performance of the DAPD:

- A power supply for the 'DAPD DC Bias' SMA port, which can reach up to 100V with accuracy of ±10mV, with an ability to restrict the maximum current flow to below ±20μA
- A temperature controller with a negative temperature coefficient (NTC) thermistor feedback loop capability (The Steinhart-Hart ABC parameters are found in the datasheet)
- 12V DC power supply for the RF amplifier with current ability to reach up to 100mA, with ±0.1V accuracy
- 4X SMA-connectorized coaxial cables, to connect to the four SMA ports of the DEM2
- An oscilloscope with a minimum of 500MHz analog bandwidth or higher (1GHz recommended)
- A calibrated short pulse light laser source (see the calibration section below)

Amplification Technologies does not supply the lab equipment. It is assumed the user has all of the required characterization equipment described above. If further assistance regarding the operation and characterization of the DAPD is needed, please contact us.

DEM2 dimensions

The DEM2 is designed to work with a DAPD - TO8. It has sockets that allow insertion and removal / replacement of DAPD-TO8. A high speed printed circuit board connects the DAPD via SMA connectors to the DAPD bias and DAPD signal out. The circuit is designed to operate in positive bias, e.g. the center pin of the SAM connector is positive with respect to the ground coaxial connection. The cathode of the DAPD is connected to the center pin, where the anode is connected to the ground, thus, the applied electric potential on the anode is lower than the electric potential applied to the cathode.

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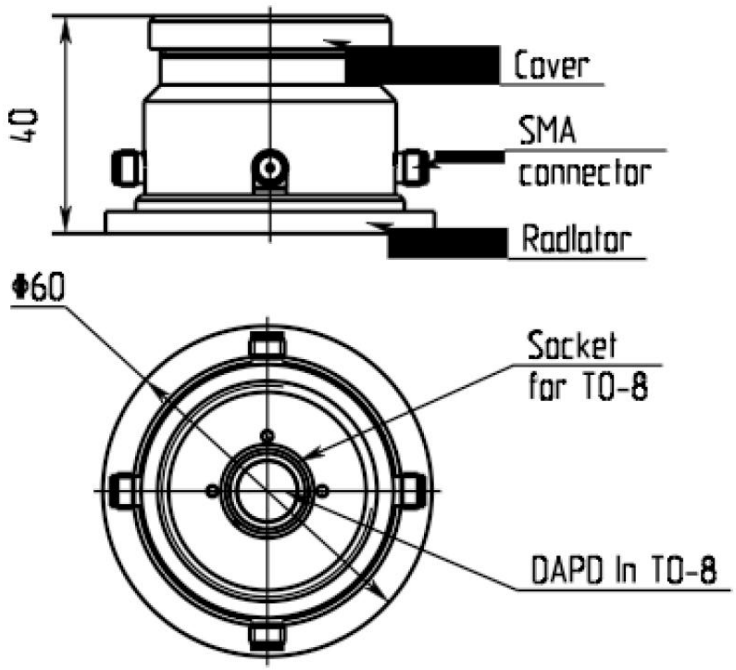
The top cap is removable with a 40mm thread. Optical lens or other standard 40mm optics apparatuses can be connected instead of the provided cap.



Electric Connection Diagram

The concept of the electronic connection recommendation is to use capacitive coupling for the output signal with the biasing circuit as described below. The improve signal extraction an inductor (with DC resistance of 510Ω) is recommended. A 10:1 capacitance ratio is used for signal extraction versus the ground capacitor, as show in the schematic diagram below (the ground capacitor is 100nF whereas the AC coupling one is 10nF).

The TEC bias and the thermistor both have floating connectors, which are not connected to the circuit ground. The circuit ground is connected to the DAPD anode.

The electric connection diagram below also includes the TO8 pin number, using the standard convention for pin numbering (see TO8 drawing figure below).

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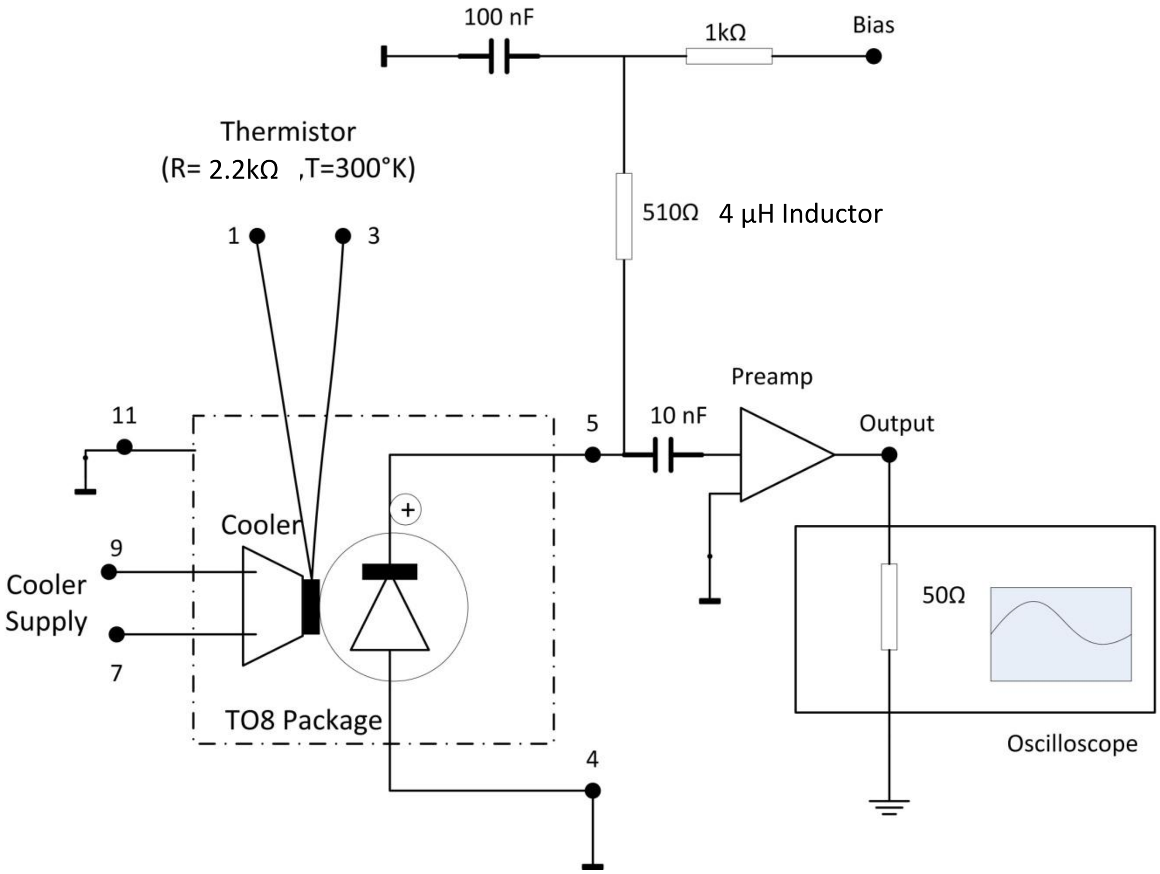
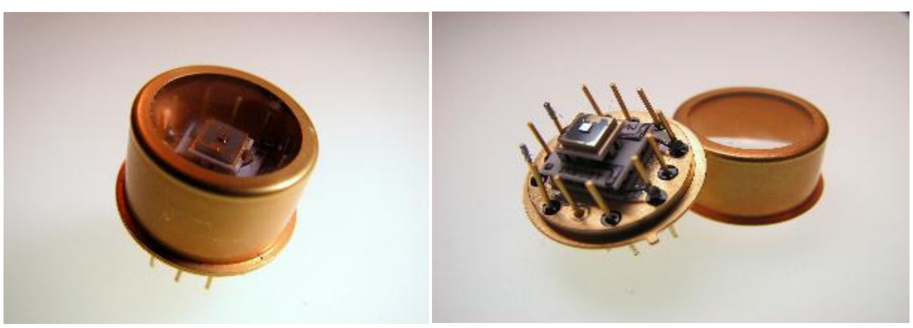


The DEM2 does not include a preamplifier. When purchasing the DEM2, Amplification Technologies provides the recommended preamplifier: e.g. Mini-Circuits ZX60-4016E-S+.

TO8 Description

The DAPD-TO8 is delivered packaged in a TO8 package with a 3-stage thermoelectric cooler and a negative temperature coefficient (NTC) thermistor, which resistance decreases with increasing temperature.



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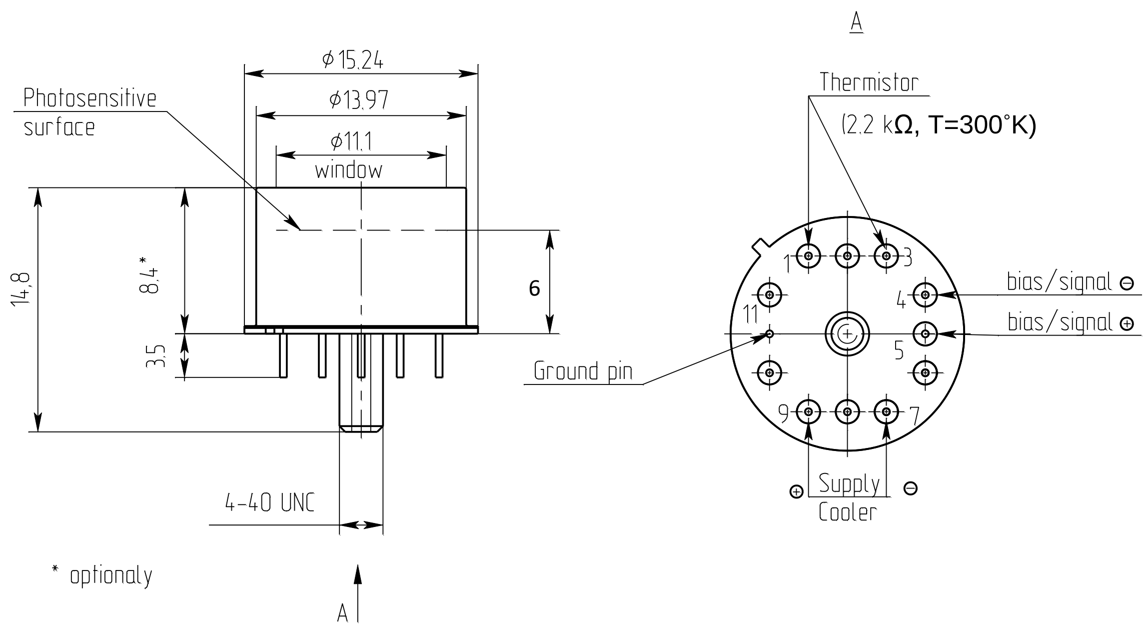
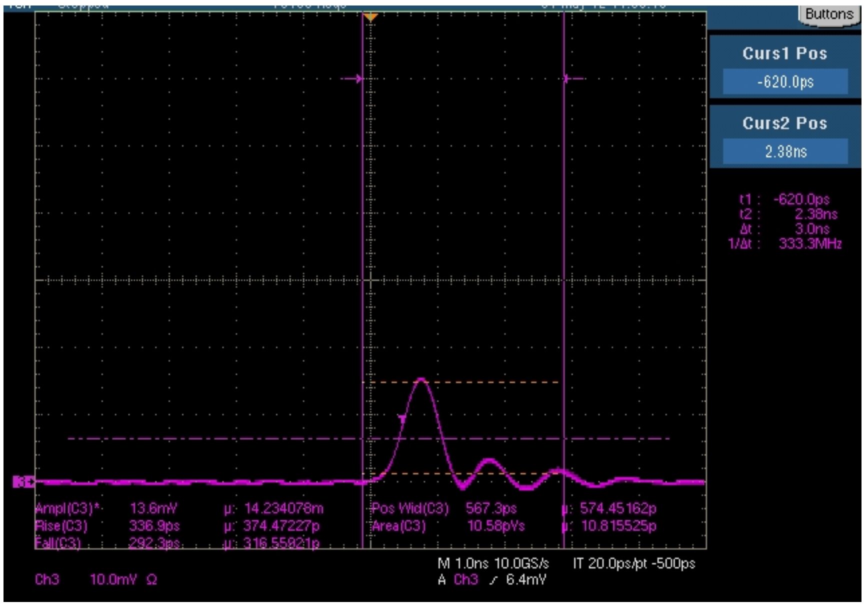
The photo above shows the 2-satge TEC version. A 3-stage version uses the same header and cap, with lower cooling elements, which place the active area of the DAPD at the same height, as with the 2-stage TEC. This can be seen in the drawing below. The height of the DAPD photosensitive surface with respect to the bottom of the TO8 is 6mm, in both TEC options.



DEM2 response curve example:

The response curve of the dark event, which is the Single Event Response (SER) is shown in the chart below. The oscilloscope scan is an average of the dark events, where a trigger level of 8mV is used. The chart is shown with 1ns per division time resolution and 10mV per division voltage resolution, using the 50Ω input of the oscilloscope. The amplifier used is the Mini-Circuits ZX60-4016E-S+.



As can be seen the pulse is positive. However this is the outcome of the inverting pre-amplifier used. It is not the outcome of applying the bias on the DAPD where the cathode is positively biased and the anode is connected to Ground, rather because the mini-Circuit ZX60 pre-amplifier use is inverting the signal. The high frequency ringing observed is caused by impedance mismatch: between the TO8, the preamplifier, and the 50Ω oscilloscope channel. The preamplifier is designed to operate with a 50Ω load; however the DAPD, as it is packaged inside the TO8, actually has lower impedance, with relatively large inductance ingredient, which is caused by the socket design, as well as the long wirebond that connects the DAPD to the TO8 pins inside the package.

Careful design of a circuit board and different packages reduce this impedance mismatch, as can be seen for example with the 5x5 array (see the 5x5 Array application notes). However, with the DEM2+TO8 combination requires placing the decision threshold voltage level for the SER above the maximum level of the ringing, which is usually at a level which is half of the SER voltage level. In the example above, the threshold is set at 8mV (half of the 16mV SER), and the maximum first reflection is 5mV.

Even with the DEM2, when the preamplifier is removed, and the DEM2 is connected directly to the oscilloscope, the matching is much improved in comparison. The Mini-Circuit ZX60 is necessary only for a low number of photons (<4). When the illumination pulse contains enough energy the DAPD amplification is sufficient to be detected in a conventional oscilloscope channel 50Ω port. This can be seen in the figure below, which shows the response to a 10-photon illumination pulse, by a 200µm-aperture DAPD, where this time there is a direct connection from the DEM2 to an oscilloscope (without a preamplifier).

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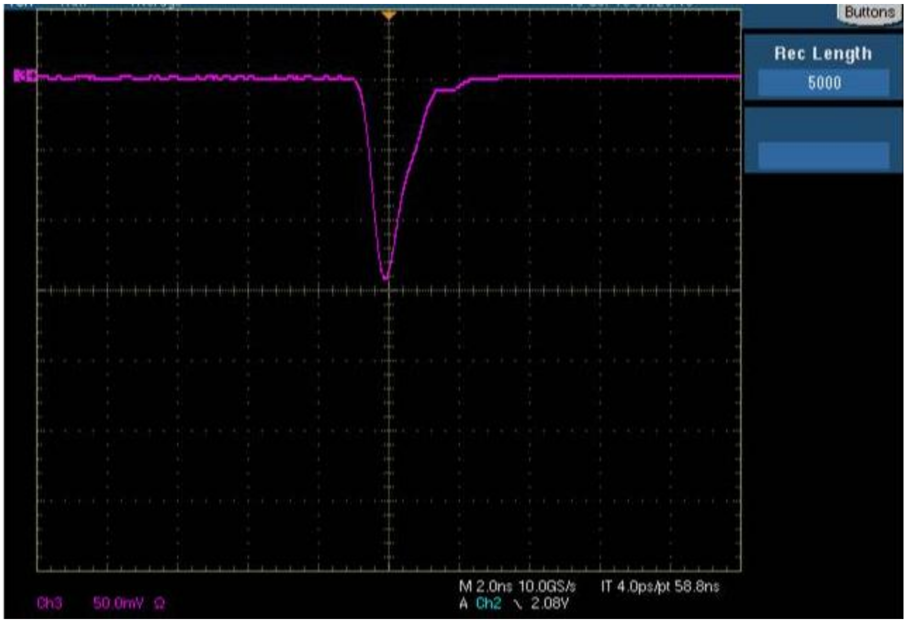

As can be seen, the pulse response is better matched with a lower-level ringing that occurs during two ~1ns cycles approximately. This time corresponds to the SMA cable length between the Oscilloscope and the DEM2. Note that the DAPD response in this scenario (without the ZX60 preamplifier) is negative. Without the preamplifier there is no pulse inversion, hence the negative response shown above.

In addition, it is of note that the higher energy pulse (which contains 10 photons), generates a response with a higher voltage level on the 50Ω system: the pulse height is 140mV. However, there is no broadening of the response: the width remains the same, approximately 1ns at half width, just as is the width of the SER.

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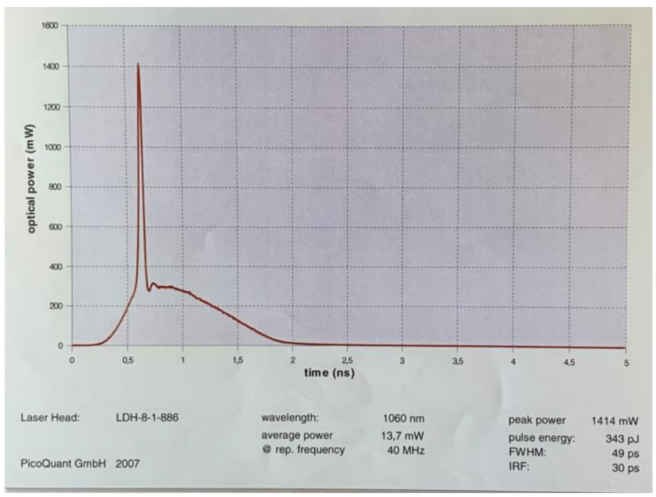
3. Testing and Characterization Procedures

Calibration of the laser source

The laser source used is a PicoQuant PDL 800-B, controller, with a LDH-C diode laser, lasing at 1060nm. The source is a diode laser operating in a Q-switched mode, with a frequency of 40 MHz, which can be divided by two to reach 20, 10, 5 or 2.5 MHz rate. In addition the driver can be externally triggered for lower rates. The pulse length is approximately 50ps, where some of the laser-pulse energy is spread over a ~1.5ns longer period, as can be seen below:



The concept of generation single-photon level pulses involves a short initial pulse duration (e.g. 50ps), and attenuation of a stable laser source to very low levels. Determining the exact (average) number of photon per pulse is done through calibration of the system.

The calibration is performed using a known (calibrated) large area photodetector with known responsivity (see details in the example below). The average power that reaches the known photodiode is then converted to photon flux which is the number of photons per second per unit area. This method is accurate as it is relying on the Photodiode's slow response and the high repetition rate of 40MHz. Dividing the flux by the repetition rate and multiplying by the DAPD under test (DUT) active area (e.g. 200µm) provides the number of photons per pulse that fall across the photosensitive area of the DAPD under test.

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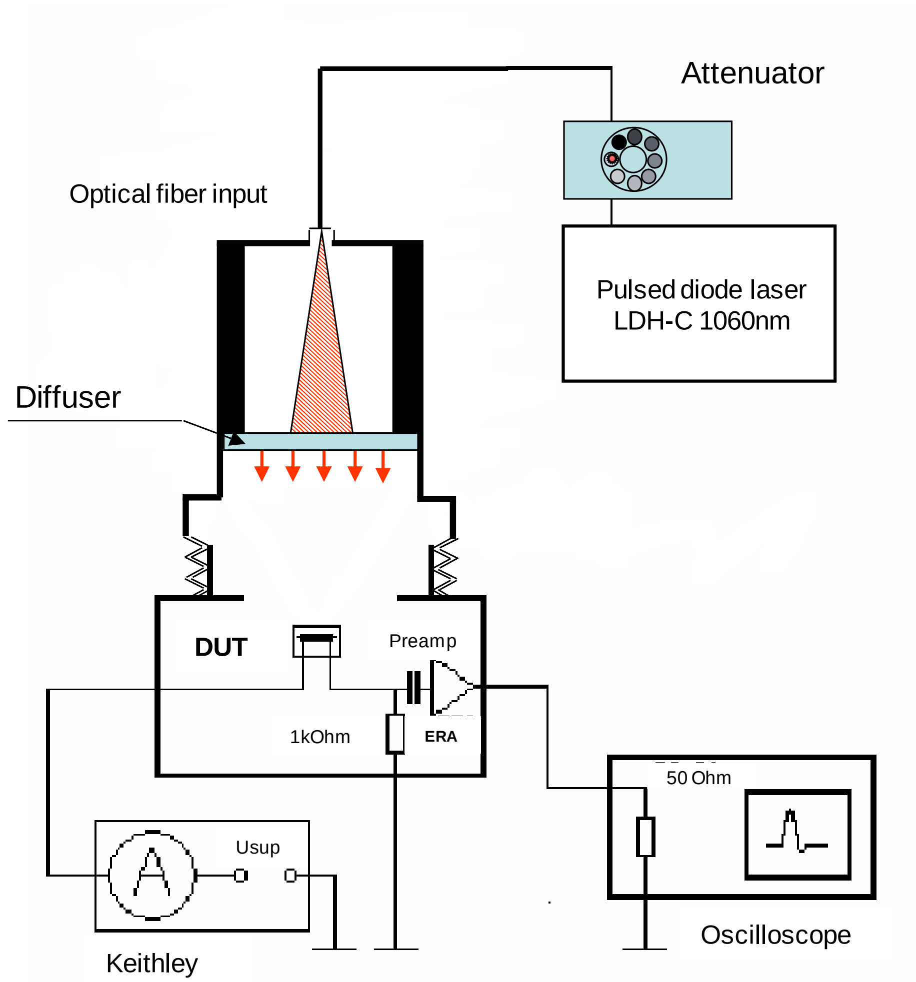
Description of the Test and Calibration Setup

The calibration and measurement setup is described in the schematics below:



The pulsed laser, 50ps 40MHz, single-mode fiber coupled, is routed though the optical attenuator. From the actuator a single-mode fiber is routed toward the optically sealed free-space optical path cylinder, which was custom-built for this test system. The cylinder is 18cmm long, with an optical diffuser placed approximately 6cm from the edge of the single-mode fiber. The system is completely dark: optically sealed with matt-black paint inside the surface, and no external light penetrates it.

The combination of the large distance from the fiber tip to the Device Under Test (DUT), with the inclusion of the diffuser in the optical path, generates a uniformly illuminated area at the DUT location. The illumination level was verified by scanning a 1cm^2 area centered on the DUT location.

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The DUT location can be populated either by a calibrated photodiode or the DAPD, where the placement of the calibrated photodiode and the DAPD under test is in the same location (+/- 100µm).

Calibration procedure calculation

Calculated number of photons per pulse using a calibrated photodiode:

The Photon Flux on the calibrated photodiode is:

$$I_{ph}/(e * \eta)$$

Thus the photons per pulse can be calculated by multiplying by the repetition rate:

$$\text{Flux} \bullet \text{Repetition-Rate}$$

Next, we account for DUT aperture dimension, with respect to the DUT:

$$(\text{Area DUT}) / (\text{Area Cal-PD})$$

In our example, the values are:

H = 29.27%
Area (Calibrated-PD; 1mm diameter) = $\pi \bullet 0.25$ (mm^2)
Area (DUT; 200µm diameter) = $\pi \bullet 0.01$ (mm^2)
Rep Rate = 40 MHz

The results of this calculation are shown in the table below:

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Example for this calculation is found in the table below:

QE	WL, nm	attenuation, dB	Rep. rate	Idark	Ilight	Iphoto	Flux/s(spot)	Flux/pulse(spot)
29.27%	1060	0	4.0E+07	-6.60E-13	-6.610E-10	6.60E-10	1.41E+10	352.505
29.27%	1060	28	4.0E+07	-6.60E-13	-4.100E-12	3.44E-12	7.35E+07	1.836
29.27%	1060	29	4.0E+07	-6.60E-13	-3.480E-12	2.82E-12	6.02E+07	1.505
29.27%	1060	30	4.0E+07	-6.60E-13	-3.010E-12	2.35E-12	5.02E+07	1.254
29.27%	1060	31	4.0E+07	-6.60E-13	-2.570E-12	1.91E-12	4.08E+07	1.020
29.27%	1060	32	4.0E+07	-6.60E-13	-2.260E-12	1.60E-12	3.42E+07	0.854
29.27%	1060	33	4.0E+07	-6.60E-13	-1.960E-12	1.30E-12	2.78E+07	0.694
29.27%	1060	34	4.0E+07	-6.60E-13	-1.730E-12	1.07E-12	2.28E+07	0.571
29.27%	1060	35	4.0E+07	-6.60E-13	-1.480E-12	8.20E-13	1.75E+07	0.438

In this example the selected attenuation level of the attenuator was 35 dB, as we usually pick a level that is approximately 0.5 photons/pulse.

Reading the "counts" from the Oscilloscope:

The oscilloscope has a built in function to count hits of pulses that fall between voltage levels and inside a time window (which is pre defined). The measurement is triggered by the laser pulse. Once the calibration of the attenuation is performed per laser pulse, it is not necessary to operate the diode laser at the highest rate of 40MHz. In fact it is preferred to operate it in a lower rate to reduce the effect of the dark event rate (DCR) and the afterpulsing (see below). The actual measurement is performed at Amplification Technologies at a 2.5MHz repetition rate.

Pulse selection parameters

We have selected a 2.5ns time window, and the threshold level to detect a photon is determined as half the size of the SER (this threshold setting level is usually ~10mV). The gate window of 2.5 is determined experimentally. It should be wide enough to include jitter effects in the DAPD as well as the diode laser and its driving electronics. In addition it has to include the full width of the DAPD response, and take into account that the Gaussian distributed single-photon can be generated from the lower emission tail of the diode laser. As can be seen above, the laser pulse is indeed short, with FWHM of ~50ps, however there is a 25% probability that the energy will arrive in a much wider timing range of ~2ns. Experimentally we viewed pulsed with higher photon level (e.g. ~10 photons per pulse), to compare the broadening effect cause by jitter and diode laser pulse broadening. The conclusion was to use a 2.5ns window setting in the determination of a "hit".

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The threshold level setting of ½ of the SER height is more straight-forward. It is set high enough to avoid counting any of the mismatch secondary pulses that appear after the main pulse as can be seen in the SER example.

We then compare the number of counted 'hits' to the number of pulses sent, multiplied by the number of photons per pulse (in the example above this factor is 0.438, as seen in the bottom line of the table), and correct it for the DCR rate, by subtracting the DCR probability.

The outcome of this calculation is the Single-Photon Detection Efficiency PDE.

After-Pulsing (AP) Contribution to the PDE

After pulsing are avoided by minimizing the gated window for the hit to be short enough to only include one pulse (~2ns). However, after pulses from a previous event that happens in the prior gating cycles, might still be present. We conduct the PDE measurement at a 2.5MHz repetition rate, which means that the pulse under consideration may include an after-pulse from the prior triggers, e.g. from 400ns, and even 800ns (two gates), prior.

Hence we cautiously state that the PDE measurement includes some afterpulsing (AP), because we cannot discern between the hits, whether they were caused by a new event or an afterpulse of a previous event. The afterpulsing occurs randomly, so the contribution of them in the exact time is very low (see the treatment of DCR below). Since the afterpulsing rate is measured to be less than 10%, we estimate the contribution of AP to be <0.1% (see DCR treatment below).

DCR Treatment when Measuring the PDE

The PDE measurement is gated. This means that the time when the response is expected is limited to the duration of the opened gate, which is 2.5ns. Hence to make sure we do not count dark events, one has to subtract the probability that a dark event occurs within the gate form the counted hits. Assuming the DCR at the bias with the best PDE is 25MGz, it means that on average, in a random fashion, there is a dark event with a duration of 1ns every 1/25MHz = 400ns. That means that 1/400 of the hits is caused by a dark event. To extend this to the worst case scenario, it is possible that the dark event falls within the entire 2.5ns hit-counting gate. Thus, the worst case scenario is that 2.5/400 = 0.00625 of the pulses (0.625%) are caused by a dark event. This is subtracted from the hit counting calculation

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4. Practical Considerations

Cooling

The heat is generated because the thermo-electric-cooler (TEC) draws energy to cool the top side, where the DAPD is. In turn it generates heat at the bottom of the TEC, which is connected to the bottom of the TO8.

The DEM2 with the receptacle for the TO8 is the heat dissipation vehicle. It is important to allow for good heat conductivity by applying heat transferring grease between the bottom of the TO8 and the heat spreading radiator that form the bottom of the DEM2. In addition, further cooling the surface that the bottom of the DEM2 makes contact to would help reduce the actual DAPD temperature. Without external cooling, with the use of thermally conducting grease, the reachable DAPD temperature with the 3-stage cooler is -55C°.

To keep a good margin from this limit, the characterization and operation recommendation allowing for environmental variations is -50°C.

Electrostatic Discharge (ESD) Precautions

The DAPD, like any photodiode with low capacitance, is very sensitive to electrostatic discharge damage. It is classified as the lowest level of the Human Body Model, which is below 249V. Hence it is defined as an electrostatic Discharge Sensitive (ESDS) device, thus special handling and proper protection is required when working with ESDS devices.

ESDS devices need proper protection of the
(1) Work area
(2) The personnel handling ESDS devices
(3) Packaging and transportation

Work area:

- It is essential to handle ESDS devices at static-safe workstations. This will prevent yield loss (through catastrophic damage) or, worse, potential reliability failures in the field (through latent damage).
- Where it is impractical or impossible to use antistatic wrist-straps or remove items that are composed of insulation materials at a static-safe workstation, use an air ionizer designed to neutralize electrostatic charges or apply topical anti-static to control generation and accumulation of static charges.

- When an air ionizer is utilized, it is vital that maintenance procedures and schedules are adhered to in order to ensure that ions generated by the ionizer are sufficiently balanced.
- Avoid bringing sources of static electricity (as shown in page 1) within 1 meter of a static-safe work bench.
- Where it is necessary to use air-guns, use special models that do not generate static charges in the air stream.

Personnel:

- Any accumulated charge on the body of the human operator should be discharged first before opening the protective container with ESDS devices inside. The discharge can be accomplished by putting a hand on a grounded surface or, ideally, by wearing a grounded antistatic wrist-strap.
- The use of an antistatic smock for each worker is highly recommended.
- Education and training on ESD preventive measures is invaluable.
- A regular audit is also helpful in supporting an ESD program.

Packaging and Transportation:

ESDS devices should be contained in a static protective bag or container at all times during storage or transportation.

Practical ESD Note: Once the DAPD is installed in a circuit, the circuit provides ESD protection. The main risk is when the devices are handled outside of their packing material and in the installation of the devices onto the circuit. For example, the DEM2 is shipped with a SMA shorting cap. The entire shipment is protected with an ESD protection package. So the DAPD is shipped to customer fully protected.