MICRO PHOTON DEVICES

PDM-IR

900 nm – 1700 nm

Infrared Photon Detection Module

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PDM-IR User Manual Version 3.1.1 - November 2019

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1 Introduction

The PDM-IR is built around a Peltier cooled InGaAs/InP Single-Photon Avalanche Diode (SPAD) for the detection of near-infrared single photons from 900 nm up to 1700 nm.

The module includes a programmable frequency and pulse generator for gating the detector, a front-end circuit for photodetector's avalanche sensing, a fast circuit for detector's avalanche current quenching and operative bias voltage resetting and some sub-circuits for signal conditioning. All the main parameters and delay paths are adjustable by the user through the software interface, in order to match the requirements of different applications. The system can be conveniently used both for counting and timing measurements, since the high-performance electronics guarantees a clean temporal response even with fast gate transitions. PDM-IR can work either in free-runnging or in gated mode (see paragraph 2) and the optical interface can be chosen between a free space and a fiber pigtailed version as shown by Figure 1 and Figure 2.

Figure 1. PDM-IR free space version.

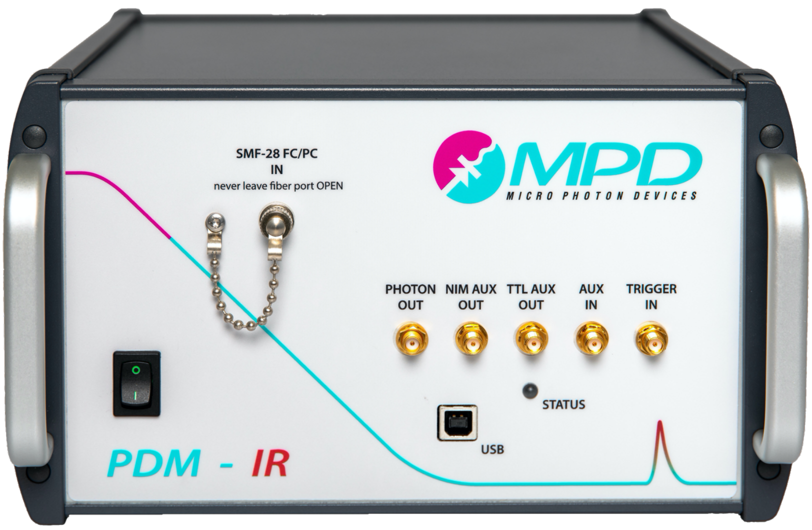

Figure 2. PDM-IR fiber pigtailed version.

2 The InGaAs/InP Single-Photon Avalanche Diode

The core of this module is a Single-Photon Avalanche Diode (SPAD), housed into the Detection Head. The detector has a 25 µm diameter active area, in case of the free space version or the pigtail one with a multimode fiber (MMF), and a 10 µm diameter SPAD the pigtail is made with a single-mode fiber. The diode is mounted on the top of a three-stage Peltier cooler. A SPAD is a p-n junction, biased well above the breakdown voltage (VB), that stays in a meta-stable state with no current flowing. At this bias, the electric field is so high that a single charge carrier injected in the depletion layer can trigger a self-sustaining avalanche. The current rises swiftly (nanoseconds or sub nanosecond rise-time) to a macroscopic steady level, in the milliAmpere range. If the primary carrier is photo-generated, the leading edge of the avalanche pulse precisely marks the photon arrival time. The current continues to flow until the avalanche is quenched by lowering the bias voltage down to or below VB. Then the bias voltage must be restored, in order to detect another photon. These operations are usually performed by a suitable circuit named Active Quenching Circuit (AQC).

The device primary source of internal noise consists in a random dark-counting rate (DCR) arising from free carriers thermally generated. These events compete with photons in triggering the detector and thus impair the signal to noise ratio. The Peltier cooler is therefore useful to lower the temperature of the detector in order to diminish this effect.

2.1 Gated Mode Operation

Normally single photon detectors are operated in the so-called free-running mode, where the devices are enabled immediately after the quenching of each avalanche current. This is true for Silicon SPADs but for InGaAs SPADs, due to higher DCR, gated regime is also used, for further reducing these unwanted counts: the detector is periodically enabled for a short time window called *Gate*, of duration T_{ON} (*Gate Width*), whereas it is usually held off at a bias slightly below the breakdown voltage.

The counting rate (CR) of a detector operated in free running, and not in gated mode, is simply the number of counts generated by the module output (PHOTON OUT) divided by the integration time:

$$CR = \frac{Number\ of\ Counts}{Integration\ Time}$$

When the detector is operated in gated mode, the photon-out count rate (CR) must be corrected considering both the *Gate Frequency*, i.e. the frequency at which the SPAD is periodically enabled, and the *Gate Width* (T_{ON}), i.e. the time length during which the SPAD is turned on during each duty cycle. The correction is due to the fact that photons (or dark-counts) may be absorbed during the times the SPAD is kept turned off and so are not counted. The correction considers how many photons have been counted and for how long, during the integration time, the SPAD has been kept really turned on. In order to calculate the true counting rate, thus, the following formula must be used:

$$CR_{DUTY} = -\frac{1}{T_{ON}} \log\,(1 - CR \cdot T)$$

where T is the *Gate Period*, i.e. the reciprocal of the *Gate Frequency*. In most of the applications, this formula can usually be approximated to:

$$CR_{DUTY} \cong CR \cdot \frac{T}{T_{ON}} \quad for \quad CR \cdot T \ll 1$$

that is the raw counts divided by the duty-cycle applied to the detector.

However, a secondary source of noise exists in SPADs: the afterpulsing. During the avalanche some carriers are captured by deep levels in the junction depletion layer and subsequently released with a statistically fluctuating delay. Released carriers can retrigger the avalanche, generating after-pulses correlated with a previous avalanche pulse which sum up with the DCR. In order to mitigate these avalanche re-triggerings, after each avalanche, during the subsequent gating occurrences, the detector is kept off for a user programmable time, named hold-off time, T_{HO}. In this way, trapped carriers released during T_{HO}, do not trigger further avalanches. The hold-off time is particularly useful when cooling the detector since the afterpulsing effect worsens at low temperatures because the decay times of the trapped carriers increase. The hold-off time is usually longer than the gate period T. Since the afterpulsing is an avalanche re-retriggering, it applies to dark counts and detected photons in the exact same way. Additionally, the afterpulsing effect can be greatly reduced, if the hold-off time is set long enough so that almost all the trapped carriers, following an avalanche, are released during the subsequent T_{HO}. In order to understand which could be this value, given a SPAD temperature and excess bias, a very simple measurement can be done: DCR is measured as a function of the hold-off time and a curve, like those shown in Figure 3, is obtained.

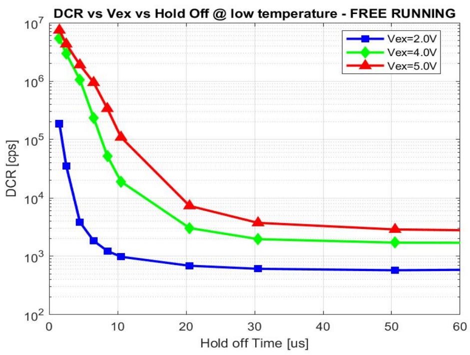

Figure 3. DCR as a function of the hold-off time for a module im free running mode at 3 different excess biases.

When the curve is flat it means that the afterpulsing is very low or negligible and the measured counting rate is the true module DCR. When the count rate increases from the flat value, it means that the afterpulsing is significant and what the user is measuring is not anymore, the DCR as previously defined, but the combined effect of the DCR and the afterpulsing.

An example of a photon counter module, operated in gated mode and employing the hold-off feature, is shown in Figure 4. The reference signal is TRIGGER GATE which sets the gate repetition rate (frequency). The signal actually applied to the SPAD is GATE, it is synchronized with TRIGGER GATE and has a width that corresponds to the T_{ON} of the SPAD. Initially GATE and TRIGGER GATE are synchronised and their pulses correspond 1-to-1. When a photon is absorbed, it triggers the avalanche current which is marked, in this example, by the falling edge of Photon Output pulse. Once the avalanche is detected it is immediately quenched; the system does not wait for the end of the Gate window to bias below breakdown the SPAD. Now GATE and TRIGGER GATE begin to differ. During the hold-off time, the TRIGGER GATE pulses are ignored, and GATE remains low, keeping the photodetector OFF. The SPAD is enabled again when the hold off time is over. Of course, if a photon arrives at the detector after the end of a previous hold-off but during the gate-off time, it is not detected as shown in Figure 4. Finally, in case the hold-off ends inside a GATE pulse, the latter is either skipped (as shown in Figure 4) or applied with a reduced width, i.e. only the remaining part of T_{ON} following the end of the hold-off. For a complete description of what happens see paragraph 4.2.

Now, because of the hold-off time, the measured counting rate CR is not equivalent to the actual rate of photons but can be estimated by:

$$CR_{HO} = \frac{CR}{1 - CR \cdot T_{HO}}$$

In counting applications, the maximum count rate should be then limited at about $1/(2T_{HO})$, because for higher values the correction factor becomes so high that even small errors in the equation's parameters will result in high errors in the CR_{HO} counting rate.

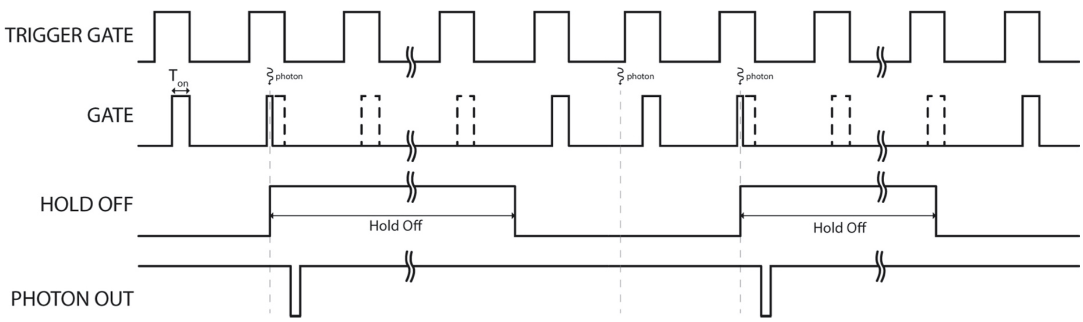

Figure 4. Main waveform in the module in case of the gated mode operation: output of pulse generator (TRIGGER GATE), pulses at the SPAD detector (GATE), hold off time keeping the detector off for the amount of time (HOLD OFF) and photon output signal (PHOTON OUTPUT).

Since the MPD PDM-IR biases the SPAD in gated mode and applies the hold-off every time an avalanche is detected, the two effects must be applied at the same time in order to obtain the correct photon counting rate CR_{photon} from the measured counting rate CR. From simple mathematics, it turns out that the final equation is the following:

$$CR_{photon} = -\frac{1}{T_{ON}} \log\left(1 - \frac{CR}{1 - CR \cdot T_{HO}} \cdot T\right)$$

which can then be simplified to:

$$CR_{photon} \cong \frac{CR}{1 - CR \cdot T_{HO}} \cdot \frac{T}{T_{ON}} \quad for \quad \frac{CR \cdot T}{1 - CR \cdot T_{HO}} \ll 1$$

Please note that the previous equations do not consider the Photon Detection Efficiency of the InGaAs SPAD. These formulas also strictly apply when the photon rate is uniformly distributed over time while particular care must be used when applied to specific cases like the one discussed in paragraph 6.1.2.

Figure 4 is, in addition, very helpful in explaining the VALID GATE output. This signal is generated in order to properly trace which TRIGGER GATE pulse effectively enabled the SPAD, i.e., which are the pulses that were not blanked during the hold-off time (VALID GATE is a digital signal with the same pattern of Gate). This information is particularly useful when looking for the percentage of counts over the total number of available valid gates. In fact, in timing measurements one must be careful not to exceed the single-photon statistics, in order not to distort the TCSPC histogram (see paragraph 6.1.2).

2.2 Free Running Operation

As already discussed, normally single photon detectors are operated in the so-called free-running mode, where the devices are enabled immediately after the quenching of each avalanche current. PDM-IR allows the user the possibility to choose which type of module operation, and thus not only the gated mode but also the free running mode is possible with PDM-IR. In this mode of operation, as shown in Figure 5, TRIGGER GATE signal is no more useful because the SPAD is always enabled until an avalanche is triggered. After each of them, the SPAD is disabled for the hold off time and then immediately and swiftly re-enabled.

Overall, as a suggestion, the gated mode is used to achieve the best Signal-to-Noise (SNR) ratios and timing resolutions whenever the signal to be detected is synchronous with a reference signal (for example the laser clock used to stimulate the signal emission) that can be used to synchronize the PDM-IR. Indeed, better S/N ratio or dynamic range, in case of TCSPC measurements, are achieved by enabling the detector only for the short windows where the signal is present and keeping the detector off whenever the signal is not present.

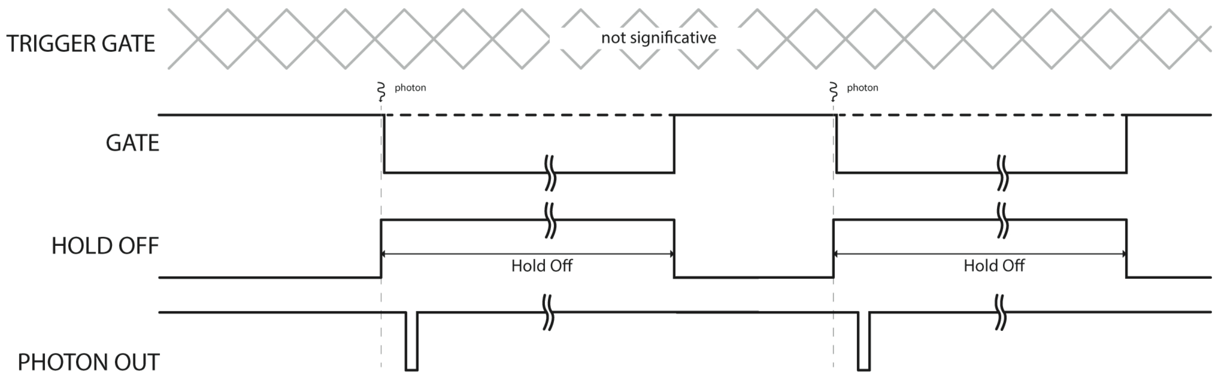

Figure 5. Main waveforms for PDM-IR module in case of the free running operation: TRIGGER GATE is not significative and ignored, the SPAD detector enabling time (GATE), the off time in case of avalanche (HOLD OFF) and photon output signal (PHOTON OUTPUT).

The free running mode is typically used instead whenever the signal to be detected is not synchronous with a reference signal (like the stimulated emission of photons from a nonlinear crystal by a CW laser). Of course, free-running mode can also be used whenever a synchronous signal has to be detected but the S/N ratio (or the dynamic range) is, in this case, lower compared to the gated mode module since the detector is always enabled and InGaAs/InP diodes have much higher noise and after pulsing, compared to the silicon diodes.

2.3 Further readings

Cova, S., Ghioni, M., Lacaita, A. L., Samori, C., and Zappa, F. "Avalanche photodiodes and quenching circuits for single-photon detection", Applied Optics, 35(12), 1956—1976 (1996). http://dx.doi.org/10.1364/AO.35.001956

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Alberto Tosi, Adriano Della Frera, Andrea Bahgat Shehata, and Carmelo Scarcella, "Fully programmable single-photon detection module for InGaAs/InP single-photon avalanche diodes with clean and sub-nanosecond gating transitions," Rev. Sci. Instrum. 83, 013104 (2012)
http://dx.doi.org/10.1063/1.3675579

3 PDM-IR hardware characteristics

3.1 Connection Panel

The PDM-IR, free space version, has USB, power connector, I/O connectors and LED on the back side, as shown in Figure 6 (left). The PDM-IR, fiber pigtailed version, has USB, I/O connectors and LED on front side and power connector on the back side as shown in Figure 6 (center and rightl). A description of each component can be found in Table 1.

Table 1. PDM-IR rear panel components

PHOTON OUT	RF output, requires 50 Ohm DC terminated transmission lines. The output is a NIM pulse, which means that the low logic level is 0 V and the high logic level is -800 mV. The falling edge of the pulse marks, with very low jitter, the photon detection time. See paragraph 4.5 for a complete electrical description of this signal.
NIM AUX OUT	RF output, requires 50 Ohm DC terminated transmission lines. The output is a NIM pulse, which means that the low logic level is 0 V and the high logic level is -800 mV. Output signal is user selectable. See paragraph 4.5 for the available possibilities and for a complete electrical description of this signal.
TTL AUX OUT	RF output, requires 50 Ohm DC terminated transmission lines. Electric pulses of 3.3V LVTTL are generated at this output. Output signal is user selectable. See paragraph 4.5 for the available possibilities and for a complete electrical description of this signal.
AUX IN	RF input, 50 Ohm with fixed DC impedance. The trigger signal can be positive or negative and the input internal threshold is fully programmable. See Table 4 for a complete electrical description of this input.
TRIGGER IN	RF input, 50 Ohm with fixed DC impedance. The trigger signal can be positive or negative and the input internal threshold is fully programmable. See Table 3 for a complete electrical description of this input.
USB ❶	Connector for a USB type-B cable. Used for PC connection
STATUS LED ❷	This LED indicates the PDM-IR status. It can be Green, Orange, Red and Off. See paragraph 4.6 for a complete description of the possible statuses
POWER SUPPLY ❸	Jack for connecting the provided power supply. It is 12 V and requires at least 15 W output power for free space version and it is 24 V and requires at least 100 W output power for fiber pigtailed version. Use only power supply provided by MPD to avoid electronics damage.
SWITCH ❹	Switch to power on/off the module

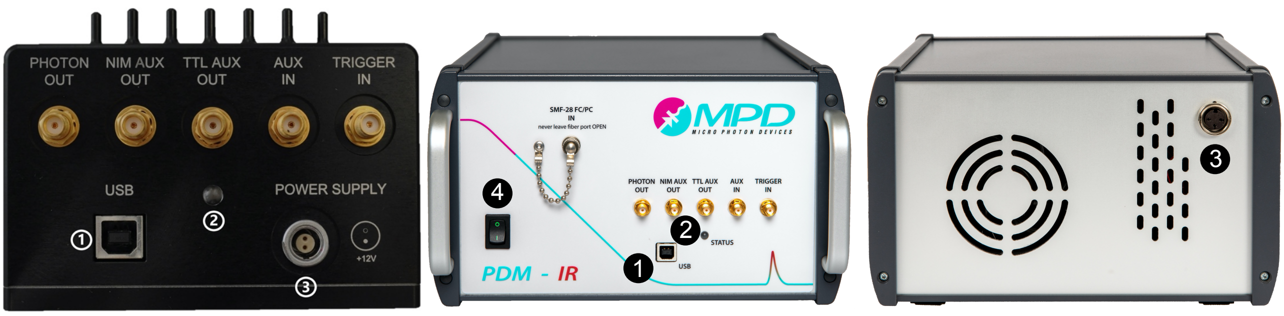


Figure 6. PDM-IR connections: free space (left) and fiber pigtailed (center-right).

3.2 PDM-IR Mechanical Dimension

Figure 7. Mechanical dimensions of the PDM-IR fiber pigtailed version.

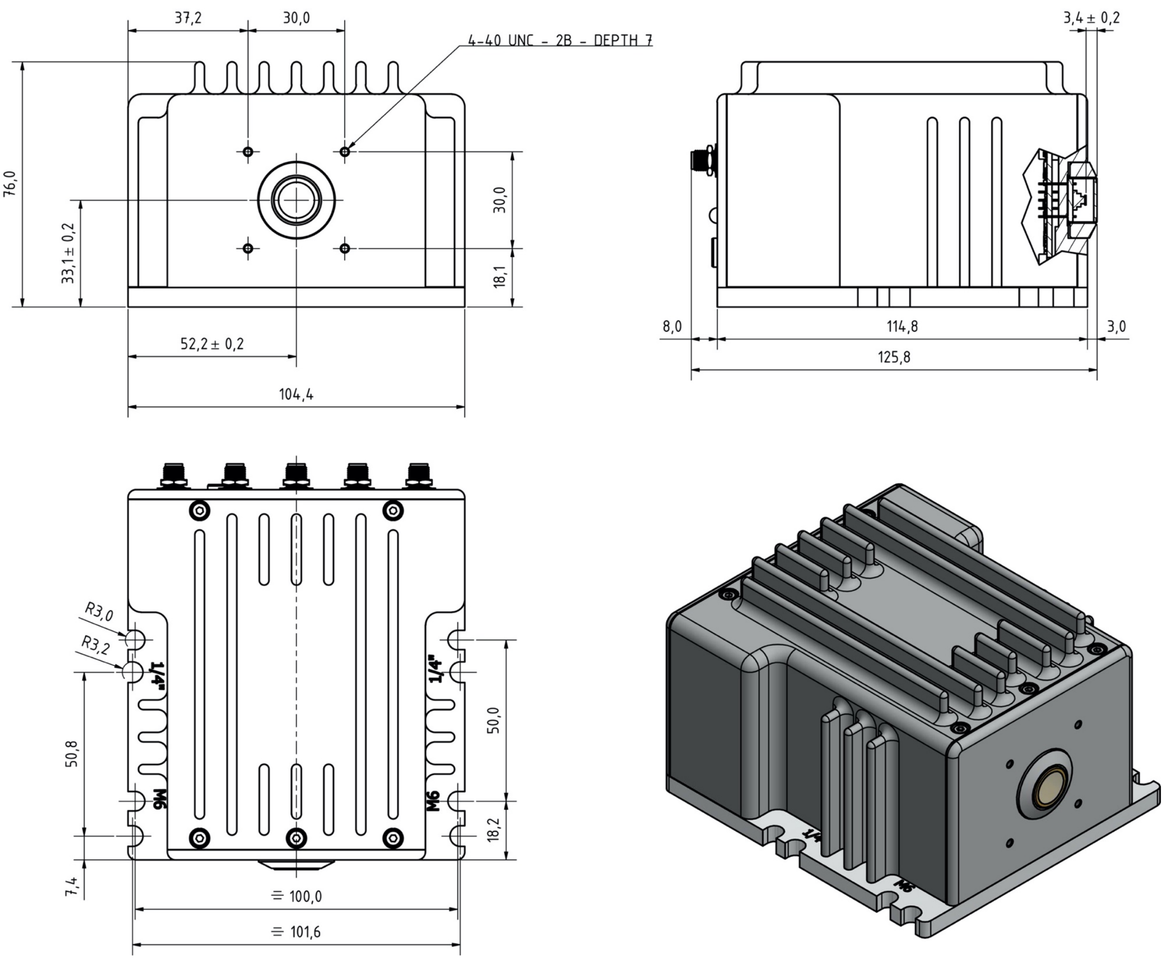


Figure 8. Mechanical dimensions of the PDM-IR free space version.

4 PDM-IR Specifications

The PDM-IR module is a complete system for photon counting in the NIR range (Figure 1, Figure 2) and it can be used either in gated or in free-running mode. Both modes of operations can be optimized through the use of several user selectable parameters, all controllable from a computer using either the delivered SDK library or the provided Windows® PC software.

When used in gated mode (see Figure 4 and paragraph 2 for details), the TRIGGER GATE signal, for GATE frequency generation, can be provided either using an INTERNAL TRIGGER or through an external signal fed into the TRIGGER IN input. In the former case, for synchronizing the GATE with other instruments, it is possible to replicate the INTERNAL TRIGGER at one of the two available outputs, depending on the desired pulse polarity, i.e. the TTL AUX OUT or the NIM AUX OUT. Complex external trigger patterns can be also fed to the TRIGGER IN input, since it accepts not only periodic but also aperiodic signals as shown in Figure 13. Additionally, it is possible to create even more complex TRIGGER GATE patterns for GATE generation, by combining the auxiliary input AUX IN signal with the INTERNAL TRIGGER or the TRIGGER IN, and by using the provided user-selectable logic functions (see paragraph 4.1 for more details). An example of such combination is shown in Figure 11. Finally, GATE signal can be generated either by exactly replicating TRIGGER GATE (Figure 14) or by creating a new signal, synchronized with the rising edge of TRIGGER GATE and with a fixed gated-ON width equal to the user set T_{ON} value (Figure 13). See paragraph 4.2 for more details. Of course, as discussed in paragraph 2, independently of the chosen trigger pattern, GATE signal is disabled for the duration of the HOLD OFF time, following each avalanche triggering. At the end of the Hold off time, two types of reset are possible depending on how the gate electronics handles what happens when the hold-off terminates inside a gate-ON time window. See paragraph 4.2 for a detailed description.

When used in free running mode (see also Figure 5 and paragraph 2), the INTERNAL TRIGGER, TRIGGER IN and AUX IN signals are meaningless and the SPAD is always on until a SPAD avalanche is initiated. In this case, the avalanche current is first quenched and then, after a well-defined hold-off, the detector is immediately enabled (see paragraph 4.2.3). Of course, in free running mode only one type of hold off reset is possible since GATE signal is always immediately enabled at the end of the hold-off time, as shown in Figure 15.

Concerning the SPAD parameters Hold-OFF time, excess bias voltage and SPAD temperature, they are all user selectable to get the best results from the measurement (see paragraph 4.3 for in-depth description).

Concerning the outputs: PHOTON OUT is the low timing jitter output signal, precisely marking the photon detection time; NIM AUX OUT and TTL AUX OUT, shouldn't be used for low jitter timing measurements and

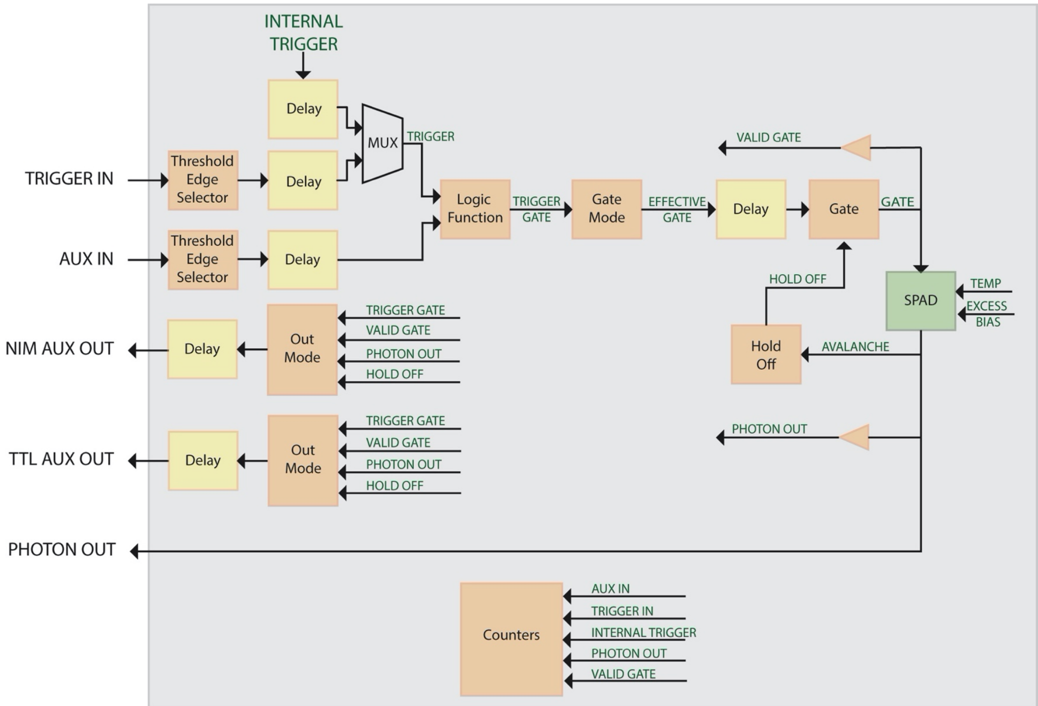


Figure 9. PDM-IR Block diagram.

the output signal can be chosen independently, on each out channel, among TRIGGER GATE, INTERNAL TRIGGER, VALID GATE, PHOTON OUT, HOLD OFF and MODULE STATUS signals (paragraph 4.5).

Independently on the chosen PDM-IR mode of operation, the module has also internal counters that continuously monitor the following signals: TRIGGER IN, AUX IN, INTERNAL TRIGGER, PHOTON OUT and VALID GATE. Specially in case of the PHOTON OUT, these counters are useful for counting applications whenever an external counter is not available (paragraph 4.4).

Finally, in the PDM-IR, all the main signal paths have a programmable delay, designed to help the user in synchronizing the various signals between them and with the external instruments. This feature is very helpful in many applications as it allows to avoid the hassle of continuously changing the cable length.

In Figure 9 the full PDM-IR block diagram is shown, while in the next paragraphs we will describe the functions and the characteristics of each subsection of it.

4.1 PDM-IR Trigger Section

This section is designed for generating the TRIGGER GATE signal that in turn is used for shaping the GATE signal actually applied to the detector. As discussed in paragraph 2, by controlling the detector in gated mode it is possible to enable the SPAD only when the signal is impinging the detector and thus increasing the SNR.

The PDM-IR offers an advanced Trigger section in order to generate trigger events only when required by the application (Figure 10). It accepts 3 signals: TRIGGER IN and AUX IN, provided by the user and INTERNAL TRIGGER, which is internally generated. The external inputs accept positive or negative signals and the threshold can be user selected with tens of mV resolution. TRIGGER IN and INTERNAL TRIGGER are mutually exclusive and can be combined with AUX IN with a user selectable logic operation in order to generate the final TRIGGER GATE. In the next paragraphs the performance of each sub-block of the Trigger section, shown in Figure 10, is illustrated.

4.1.1 Internal Trigger

The INTERNAL TRIGGER is an internally created waveform with a periodic pattern with fixed frequency (selectable by the user) and a duty cycle equal to 50%. In order to be able to synchronize the PDM-IR module with other instrumentations, set the TTL AUX OUT and/or the NIM AUX OUT to output the INTERNAL TRIGGER. In Table 2 the Electrical characteristics of the INTERNAL TRIGGER are illustrated.

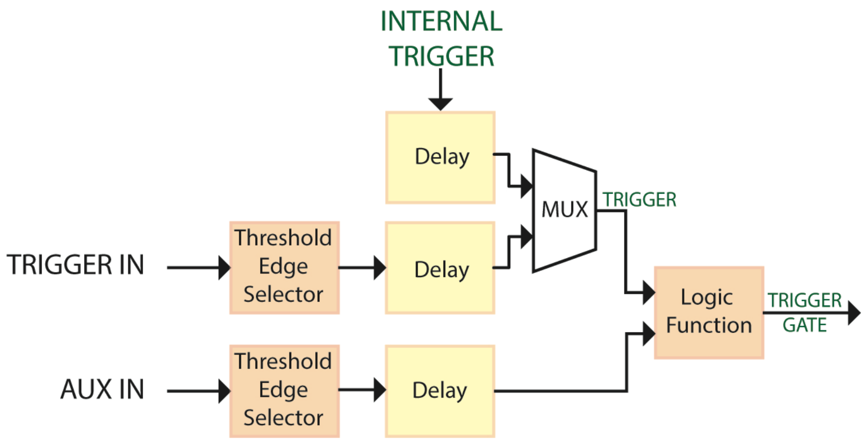


Figure 10. PDM-IR Trigger Section Block diagram.

Table 2. Internal trigger specifications

Parameter	Symbol	Description	Min.	Typ.	Max.	Unit
Internal Trigger Frequency	$freq_{IN}$		100		100 M	Hz
Internal Trigger Frequency Step	$\Delta freq_{IN}$			1		Hz
Frequency Total Stability			-100		100	ppm
Internal Trigger Duty Cycle			40	50	60	%
Internal Trigger Delay	$\delta_{INT\_TRIGGER}$		0		100	ns
Internal Trigger Delay step				1		ns

4.1.2 Trigger In

The TRIGGER IN, provided by the user, can be periodic or aperiodic, positive and/or negative. It's normally used to synchronize the GATE signal of the PDM-IR with a LASER source that cannot be triggered. The user can set the threshold voltage and the significative edge. In Table 3 the Electrical characteristics of the TRIGGER IN input are illustrated.

Table 3. Trigger In specifications

Parameter	Symbol	Description	Min.	Typ.	Max.	Unit
Trigger In Max Frequency			100 M			Hz
Trigger In Delay	$\delta_{TRIGGER\_IN}$		0		100	ns
Trigger In Delay step				1		ns
Trigger In high voltage	V_{IH_IN}				3	V
Trigger In low voltage	V_{IL_IN}		-2			V
Trigger In differential range	V_{ID_IN}		-2		2	V
Trigger In termination	R_{IN_IN}			50		Ω
Trigger In voltage overdrive	V_{OV_IN}		100			mV
Trigger In pulse width	$t_{IN\_PULSEmin}$		800			ps
Trigger In Slew Rate	SR_{IN}		10			V/µs
Trigger In Edge				Neg/pos		
Trigger In Threshold	V_{TH_IN}		-2		2	V
Trigger In Threshold resolution	ΔV_{TH_IN}			10		mV

4.1.3 Aux In

The AUX IN input is provided by the user, can be periodic or aperiodic, positive and/or negative. It's an auxiliary signal, useful to enable or disable the SPAD in certain conditions. Threshold voltage and significative edge can be set by the user. The logic function between AUX IN and TRIGGER (see Figure 10) can be for example very useful in some measurements, like cross-correlation ones (see paragraph 6.2.1). Figure 11 shows an example of what happens in case of an aperiodic and complex TRIGGER IN is combined with the shown AUX IN signal by means of a OR logic port which generates the TRIGGER GATE. The same figure shows the case where the TRIGGER GATE is generated combining TRIGGER IN and AUX IN with an AND logic. In Table 4 the Electrical characteristics of the AUX IN input are illustrated.

Table 4. Aux In electrical specifications.

Parameter	Symbol	Description	Min.	Typ.	Max.	Unit
Aux In Max Frequency			100 M			Hz
Aux In Delay	δ_{AUX_IN}		0		100	ns
Aux In Delay step				1		ns
Aux In high voltage	V_{IH_AUX}				3	V
Aux In low voltage	V_{IL_AUX}		-2			V
Aux In differential range	V_{ID_AUX}		-2		2	V
Aux In termination	R_{IN_AUX}			50		Ω
Aux In voltage overdrive	V_{OV_AUX}		100			mV
Aux In pulse width	t_{IN_AUX}		800			ps
Aux In Slew Rate	SR_{AUX}		10			V/µs
Aux In Edge				Neg/pos		
Aux In Threshold	V_{TH_AUX}		-2		2	V
Aux in Threshold resolution	ΔV_{TH_AUX}			10		mV

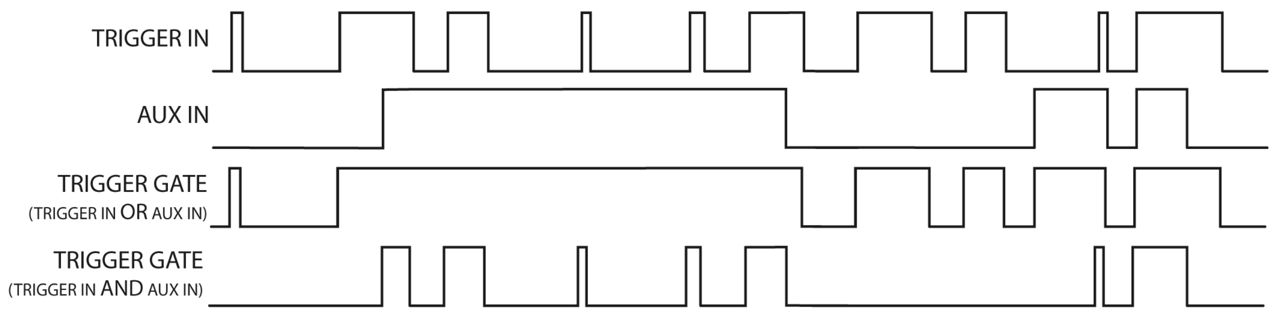


Figure 11. Advance trigger section using AUX IN signal in logic function with TRIGGER IN signal. TRIGGER GATE is shown in case of use the OR port and the AND port between the two signals.

4.1.4 Logic Function

The Logic Function Block allows advanced gate triggering using TRIGGER (selected between TRIGGER IN and INTERNAL TRIGGER) and AUX IN as inputs. The Logic Function can be AND, OR or XOR. The two inputs and the output can also be inverted if needed. Figure 11 shows an example of combination between TRIGGER IN and AUX IN signals in case OR or AND logic is used.

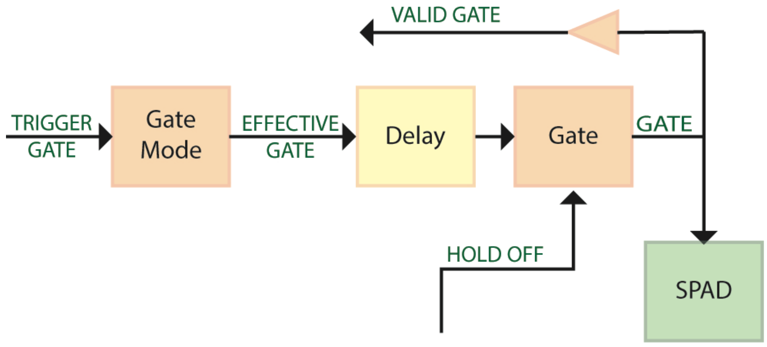


Figure 12. PDM-IR Gate Section Block diagram.

4.2 PDM-IR Gate Section

The TRIGGER GATE signal (see Figure 12), coming from the PDM-IR Trigger Section (4.1), is shaped in order to generate the desiderated gate width and frequency, i.e. the EFFECTIVE GATE. The PDM-IR offers also three possible mode of generating the EFFECTIVE GATE signal and thus of operation:

1. For each TRIGGER GATE rising edge, a fixed gate width, set by the T_{ON} parameter, is generated (described in 4.2.1);
2. EFFECTIVE GATE replicates the TRIGGER GATE waveform (see paragraph 4.2.2);
3. The module works in free running mode and thus becomes TRIGGER GATE independent (see 4.2.3).

The EFFECTIVE GATE, whose electrical characteristics are shown in Table 5, can also be delayed before being applied to the SPAD. The GATE signal is thus the EFFECTIVE GATE after a user controllable delay and with the HOLD-OFF, also user controllable, applied after every avalanche triggering. As GATE depends on the actual photon flux, it can only be monitored through the VALID GATE signal. Finally, as HOLD-OFF plays an important role in GATE generation, it is also here discussed, while its possible selectable values are shown in paragraph 4.3.3.

Table 5. Gate electrical specifications.

Parameter	*Symbol*	*Description*	*Min.*	*Typ.*	*Max.*	*Unit*
Effective Gate Max Frequency			100M			Hz
Effective Gate Delay	$\delta_{EFFECTIVE\_GATE}$		0		100	ns
Effective Gate Delay step				1		ns
Gate Window	t_{ON}		1 n		1.5 m	s
Gate Window Step	ΔT_{ON}			1		ns

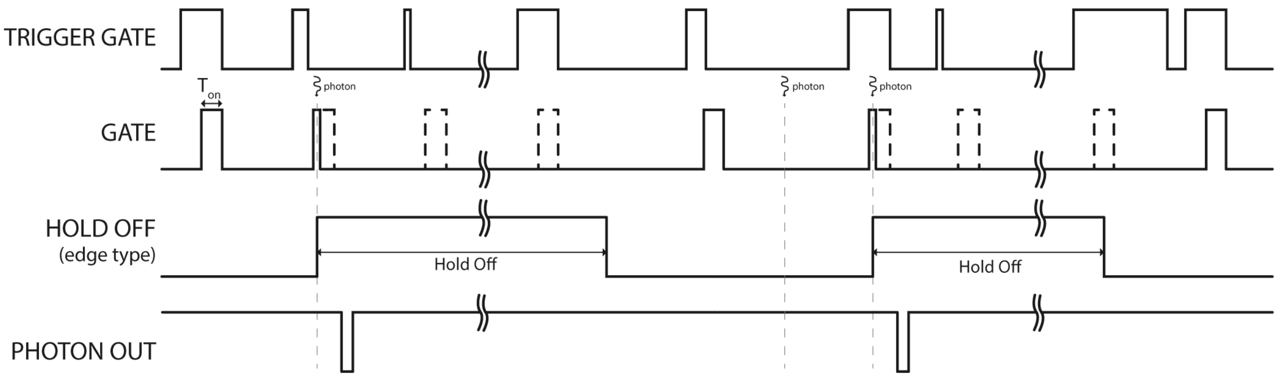


Figure 13. Typical signals in Gated mode with fixed gate width operation and hold-off set to HOLD OFF EDGE (i.e. gate pulses that even partially overlap with the hold off are skipped).

4.2.1 Gated mode with fixed gate width operation

In this operating mode, shown in Figure 13, the PDM-IR generates a gate window, with a fixed width equal to T_{ON}, for each TRIGGER GATE rising edge. In case of a photon detection (or in general an avalanche triggering), while at PHOTON OUT a pulse is generated for marking the photon arrival time, the GATE signal is swiftly disabled for a period equals to the set HOLD-OFF time and all trigger events during this time are masked. At the end of the Hold off time, two types of reset are possible depending on how the gate electronics handles what happens when the hold-off terminates inside a gate-ON time window.

More precisely, the Hold Off can be synchronized with the EFFECTIVE GATE signal (HOLD OFF EDGE) or can be set asynchronous (HOLD OFF LEVEL). With the HOLD OFF EDGE modality, the first gate window to be applied to the SPAD, following the end of a HOLD-OFF, is the first one to have its rising edge positioned in time after the end of the hold-off, as shown in Figure 13. In this case, as shown in Figure 13, the gate window, that happens across the time instant that the HOLD-OFF ends, is skipped. The use of HOLD OFF EDGE is thus a safe condition because it ensures that all the applied gate pulses have the same width, i.e. the set T_{ON}. It follows that the equations discussed in paragraph 2 can be applied seamlessly and that the user does not incur in any measurement distortion, especially in case of high photon fluxes and in correlation measurements.

With the HOLD OFF LEVEL modality the SPAD can be immediately enabled at the end of the hold-off, if the status of GATE is high, as shown in Figure 14. For example, if the hold-off ends in the middle of a GATE window, the latter is not skipped as before, but the SPAD is enabled starting from the end of the HOLD OFF and stopping, as usual, with the end of this particular GATE window. In a simpler way, GATE will always follow the EFFECTIVE GATE pattern, immediately as the hold off ends.

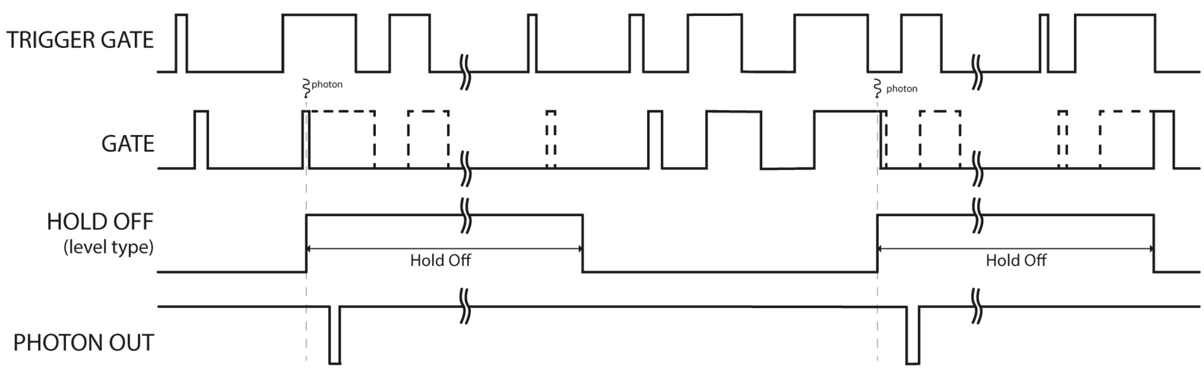


Figure 14. Typical signals in Gated mode with Free-gate operation and hold-off set to HOLD OFF LEVEL.

In this case non-standard gates are generated which may lead to measurement errors at high photon fluxes and in other cases. For this reason, this modality is normally more useful if used in conjunction with the free-gate mode of operation (see paragraph 4.2.2).

Finally, it is worth noting that, in gated-mode with fixed gate width, after an avalanche triggering, GATE signal is left disabled until the next GATE pulse, even if T_{ON} is longer than the hold-off time. In other words, in this gate modality, only the first event inside a gate-on window is recorded.

4.2.2 Gated mode with Free-gate operation

In gated mode with Free-gate operation (Figure 14), the PDM-IR works like the previous mode, generating a gate window for each trigger event, but GATE pulses replicate exactly those of TRIGGER GATE, apart of course when the HOLD OFF is applied. In fact, in this mode of operation TRIGGER GATE and EFFECTIVE GATE are identical. Even in gate-mode with Free-gate operation, in case of photon detection, all GATE windows that occur during a HOLD OFF are masked. Finally, even with this mode of operation HOLD OFF LEVEL and HOLD OFF EDGE can be chosen. In Free-gate operation, opposite to the gated mode with fixed width, it is possible to have multiple triggers inside a T_{ON} window when T_{ON} is longer than the set HOLD OFF (normally TON >> HOLD OFF). Of course, in order to unlock this possibility, the HOLD OFF LEVEL should be set as, only in this case, when the HOLD OFF ends the GATE is immediately applied if the TRIGGER GATE is high. In this way it is possible thus to count more than 1 photon per gate, useful in some particular applications.

4.2.3 Free running mode

In free running mode, as shown in Figure 15, the SPAD is always enabled and it is TRIGGER GATE independent. In case of photon detection, the SPAD is disabled during the hold off time, but at the end of it is swiftly is re-enabled. Of course, in this case only the HOLD OFF LEVEL setting is allowed.

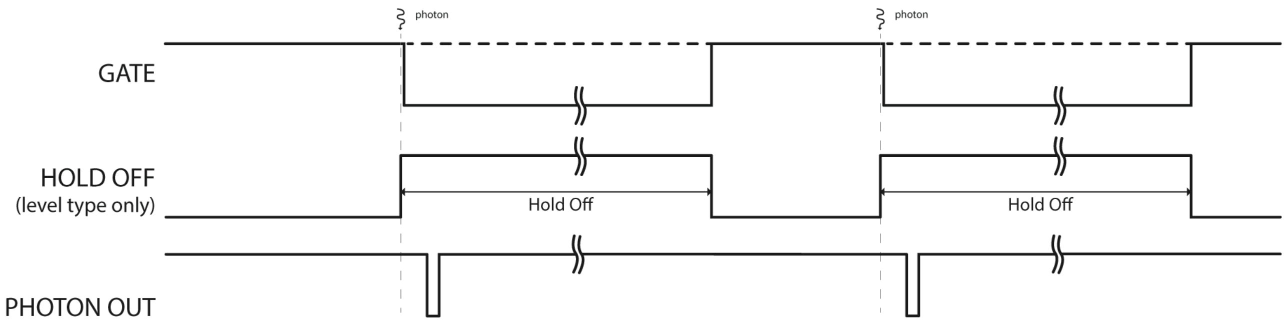


Figure 15. Typical signals in Free running mode.

4.3 PDM-IR SPAD Section

After having discussed how the internal PDM-IR circuitry control the SPAD operation, the last component of the PDM-IR to be discussed is the SPAD itself. Indeed, in order to get the best performance from the SPAD, the user should be allowed to adjust the SPAD main parameters. For this reason, PDM-IR allows the control of both the SPAD working temperature and the Excess Bias voltage. The lower temperature, the lower the DCR but the higher the afterpulsing effect, given a hold off time, as the trap decay times increase. Of course, when setting the lowest SPAD temperatures, the PDM-IR must be placed on a good heatsink, so that it can dissipate the heath generated by the Peltier cooler. If this is not done, the module might heat up too much and go in safe mode shutting down the detector operation. In Figure 16 section of the PDM-IR block diagram related to the SPAD is showed.

In the next paragraphs, the 3 parameters related to the SPAD setting are discussed in detail: SPAD temperature, SPAD excess bias voltage and SPAD hold off. In Table 6, the possible settings and their allowed range of operation, are showed.

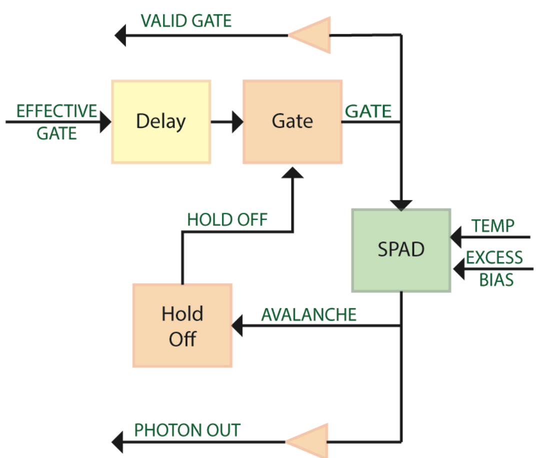


Figure 16. PDM-IR SPAD Section Block diagram.

4.3.1 Temperature

The user can select the working temperature among 4 different predefined values:

- High temperature (243K): the dark count rate is the highest than other temperature modes, but no particular caution is required for module thermal stability.
- Medium temperature (233K): the DCR is the one shown in the test report.
- Low temperature (229K): the dark count rate is very low.
- Lowest temperature (225K): the dark count rate is the lowest as possible. When operating the SPAD of a PDM-IR with this setting, a low ambient temperature (~22-23°C) is required.

Please note that when using the PDM-IR free space version, the module requires a good heath sink (the better, the lower the set SPAD temperature) for optimal module thermal dissipation and uninterrupted operation.

4.3.2 Excess Bias

The excess bias is the difference between the SPAD bias voltage, and its breakdown and it controls directly the SPAD performance: the higher the Excess Bias, the higher the Photon Detection Efficiency (PDE) the better the timing resolution but the higher the DCR. As the DCR increases more than linearly while the PDE increases linearly or less than linearly, the best trade off should be found for each measurement set-up.

4.3.3 Hold Off

The hold-off has been already extensively discussed both in paragraph 2 and in paragraph 4.2, so we remind here only to its specifications shown in Table 6.

Table 6. SPAD specifications.

Parameter	Symbol	Description		Min.	Typ.	Max.	Unit
Excess Bias	V_{EX}	Gated mode with fixed gate width		2		7	V
		Gated mode with Free-gate AND Free running mode		2		5	V
Excess Bias Step	ΔV_{EX}				100		mV
Hold Off	t_{HO}			1		3000	us
Hold Off step	Δt_{HO}				10		ns
SPAD DCR	DCR	V_{EX} = 2 V, Temp = "Low", free running operation, Hold off time = 100 µs	Free Space module		5 k	10 k	cps
			SMF-28 pigtailed module		0.5 k	1 k	cps
			MMF-50GI pigtailed module		5 k	10 k	cps
SPAD active area		Free space			25		µm
Pigtailed SPAD fibers		Single-mode fiber		SMF-28			
		Multi-mode fiber		MMF-50GI			

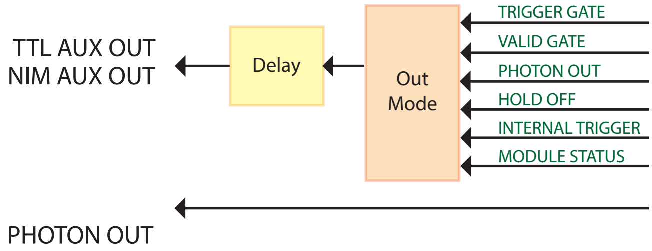


Figure 17. PDM-IR Output Section Block diagram.

Table 7. Counters specifications

Parameter	Symbol	Description	Min.	Typ.	Max.	Unit
Counter Integration Time			0.1		60	s
Counter Integration Time step				20		ms
Counter Max Frequency			100			MHz

4.4 PDM-IR Counters Section

The PDM-IR integrates 5 counters to analyze the major signals: AUX IN, TRIGGER IN, INTERNAL TRIGGER, PHOTON OUT, VALID GATE. Every counter stores data counts accumulated during counter integration time; In order to avoid missed readings, specially at short integration time, the count data are stored in a 20 positions circular array, that are automatically read from the VisualPDM-IR software or that can be read by using the provided SDK. The counter characteristics are shown in Table 7.

4.5 PDM-IR Output Section

The PDM-IR provides the PHOTON OUT output and two user-selectable outputs: a positive LVTTL output and a negative NIM output. Both outputs can be selected among the following signals: TRIGGER GATE, VALID GATE, PHOTON OUT, HOLD OFF, INTERNAL TRIGGER and MODULE STATUS, as shown in Figure 17. The module status is high in case of module error (it is the equivalent of the red led, see paragraph 4.6). The outputs are RF output: they require 50 Ohm transmission line coaxial cable and a 50 Ohm termination to properly work. Electrical specifications of the three signals are shown in Table 8.

Table 8. Outputs specifications.

Parameter	Symbol	Description	Min.	Typ.	Max.	Unit
NIM Aux Out low logic level	V_{OH_NIM}	50 Ω termination required		0		V
NIM Aux Out high logic level	V_{OL_NIM}	50 Ω termination required		-800		mV
NIM Aux Out bandwidth			100			MHz
NIM Aux Rise/Fall Time		20-80%		400		ps
NIM Aux Delay	δ_{NIM_AUX}		0		100	ns
NIM Aux Delay step				1		ns
TTL Aux Out low logic level	V_{OH_TTL}	50 Ω termination required		0		V
TTL Aux Out high logic level	V_{OL_TTL}	50 Ω termination required	2.4		3.3	V
TTL Aux Rise/Fall Time		20-80%		1		ns
TTL Aux Out bandwidth			100			MHz
TTL Aux Delay	δ_{TTL_AUX}		0		100	ns
TTL Aux Delay step				1		ns
Photon Out low logic level	V_{OH_NIM}	50 Ω termination required		0		V
Photon Out high logic level	V_{OL_NIM}	50 Ω termination required		-800		mV
Photon Out Rise/Fall Time		20-80%		400		ps
Photon Out Pulse width				10		ns

4.5.1 PHOTON OUT

The PHOTON OUT generates an output pulse, according to the NIM standard, with low timing jitter. In this way it precisely marks the photon arrival time. It has a fixed delay between the photon arrival time and a specific output connector (see paragraph 4.7). The photon detection is marked by the signal falling edge from 0V to -800mV providing -16 mA current in a DC grounded 50 Ohm termination. The low-level signal (-800 mV) is voltage protected and cannot provide a lower voltage, in case of unterminated lines. Moreover, the use of unterminated transmission lines corrupts the rising edge of the signal and, as a result, the signal becomes unusable. This output is specifically designed to be used in combination with the most common available TCSPC instrumentation available in the market.

4.5.2 TTL AUX OUT

The TTL AUX OUT offers the possibility to interface and sync the PDM-IR with other instruments; in fact, the LVTTL output levels (0 ÷ 3.3 V) allows to communicate with standard CMOS electronics.

4.5.3 NIM AUX OUT

The auxiliary output NIM AUX OUT is the negative levels signal (from 0 to -800mV providing -16 mA current in a DC grounded 50 Ohm termination). The low-level signal (-800 mV) is voltage protected and cannot provide a lower voltage, in case of unterminated lines. Moreover, the use of unterminated transmission lines corrupts the rising edge of the signal and, as a result, the signal becomes unusable.

4.6 PDM-IR LED Status

The PDM-IR has a LED lens on the rear panel for showing the current module status. Table 9 shows the LED colors and their meanings. Unless the PDM-IR has detected a serious error that is signaled with a RED colored LED, the standard condition for the LED status is OFF. For this reason, it is important to understand the LED color sequence during the most common procedures with the PDM-IR, like changing module parameters. These typical sequences are described in Table 10.

Table 9. LED color meaning.

OFF LED	when the LED is OFF, there are 2 possibilities: the module is not powered-ON or the module is correctly working and the SPAD is enabled.
BLINKING ORANGE	a blinking orange LED indicates that the PDM-IR is powered-ON but the SPAD is not polarized. This state is active for less than 10 seconds after powering-ON the module or whenever the SPAD has been turned off using the SDK or the VisualPDM-IR software.
ORANGE LED	when the LED shows a stable Orange color, the PDM-IR is updating the its internal working parameters (SPAD ON/OFF status, free-running/gated working mode, gate parameter, …). At the end of any update procedure, the LED will always change to GREEN, if the update procedure completes successfully with the SPAD enabled, to BLINKING ORANGE if the update procedure completes successfully with the SPAD disabled or to RED LED if there is an error.
GREEN LED	this LED color is used when the SPAD is correctly polarized and ready to detect photons. The green color is always active only for 5 seconds to report the success of an update procedure; after that, the LED will change status to the OFF state in order to avoid measurement errors due to an unwanted light source.
RED LED	when red color is active, the SPAD is disabled for safety precautions as an error occurred. In order to understand what happened, use the SDK or the VisualPDM-IR for reading the error type.

Table 10. Examples of LED colors sequence during common procedures on the PDM-IR.

Procedure/Action	***Initial condition***	***LED sequence***	***Final Condition***
Switching on the PDM-IR	PDM-IR not powered	- OFF - BLINKING ORANGE for 10 seconds - ORANGE until SPAD ON - GREEN for 5 seconds - OFF	SPAD ON
Updating a parameter	SPAD ON	- OFF/ORANGE/GREEN* - ORANGE until parameters updated - GREEN for 5 seconds - OFF	SPAD ON, parameter updated
Updating a parameter	SPAD OFF	- BLINKING ORANGE	SPAD OFF, parameter updated
Updating a parameter while setting a value out of its limit	any	- no changes	no parameter updated
TURNING ON SPAD	SPAD OFF	- BLINKING ORANGE - ORANGE until SPAD ON - GREEN for 5 seconds - OFF	SPAD ON
TURNING OFF SPAD	SPAD ON	- OFF/ORANGE/GREEN* - ORANGE until SPAD OFF - BLINKING ORANGE	SPAD OFF

* with PDM-IR all parameter can be updated at any time, i.e. after the SPAD has been successfully turned on (LED OFF), when the module is currently updating parameters (LED ORANGE), or when the module as just (within less than 5s) updated a parameter (LED GREEN).

4.7 PDM-IR propagation delays

Table 11 shows the intrinsic propagation delays between the major signals. The propagation delays are typical values and accurate within +/- 5 ns and they have been measured with all the programmable delays set to 0 ns.

Table 11. Propagation delays of main signals

Input signal	*Output signal*	*Propagation delay*
TRIGGERN IN	GATE	30 ns
	TTL AUX OUT (as TRIGGER GATE)	28 ns
	NIM AUX OUT (as TRIGGER GATE)	26 ns
TRIGGER AUX	GATE	30 ns
	TTL AUX OUT (as TRIGGER GATE)	28 ns
	NIM AUX OUT (as TRIGGER GATE)	26 ns
GATE	TTL AUX OUT (as VALID GATE)	12 ns
	NIM AUX OUT (as VALID GATE)	14 ns
TTL AUX OUT (as INTERNAL TRIGGER)	GATE	14 ns
NIM AUX OUT (as INTERNAL TRIGGER)	GATE	12 ns
HOLD OFF	TTL AUX OUT (as HOLD OFF)	18 ns
	NIM AUX OUT (as HOLD OFF)	16 ns
PHOTON	PHOTON OUT	5 ns
	TTL AUX OUT (as PHOTON OUT)	22 ns
	NIM AUX OUT (as PHOTON OUT)	20 ns

5 PDM-IR Software Interface

The PDM-IR is provided with a control software, which runs on Microsoft Windows operating systems: VisualPDM-IR. This software provides a direct access to PDM-IR settings.

5.1 *Installation*

Connect the PDM-IR to the PC. If the drivers are not automatically installed by windows® OS, download them from FTDI website (https://www.ftdichip.com/Drivers/D2XX.htm) and install them manually. Please note that USB driver needs to be correctly installed prior the software installation. Double-click the desired installer (32-bit or 64-bit) and follow the guided installation procedure.

5.2 *Software Interface*

The VisualPDM-IR interface is composed by a main window divided in several sections as shown in Figure 18, and a satellite window for each active counter (see Figure 24).

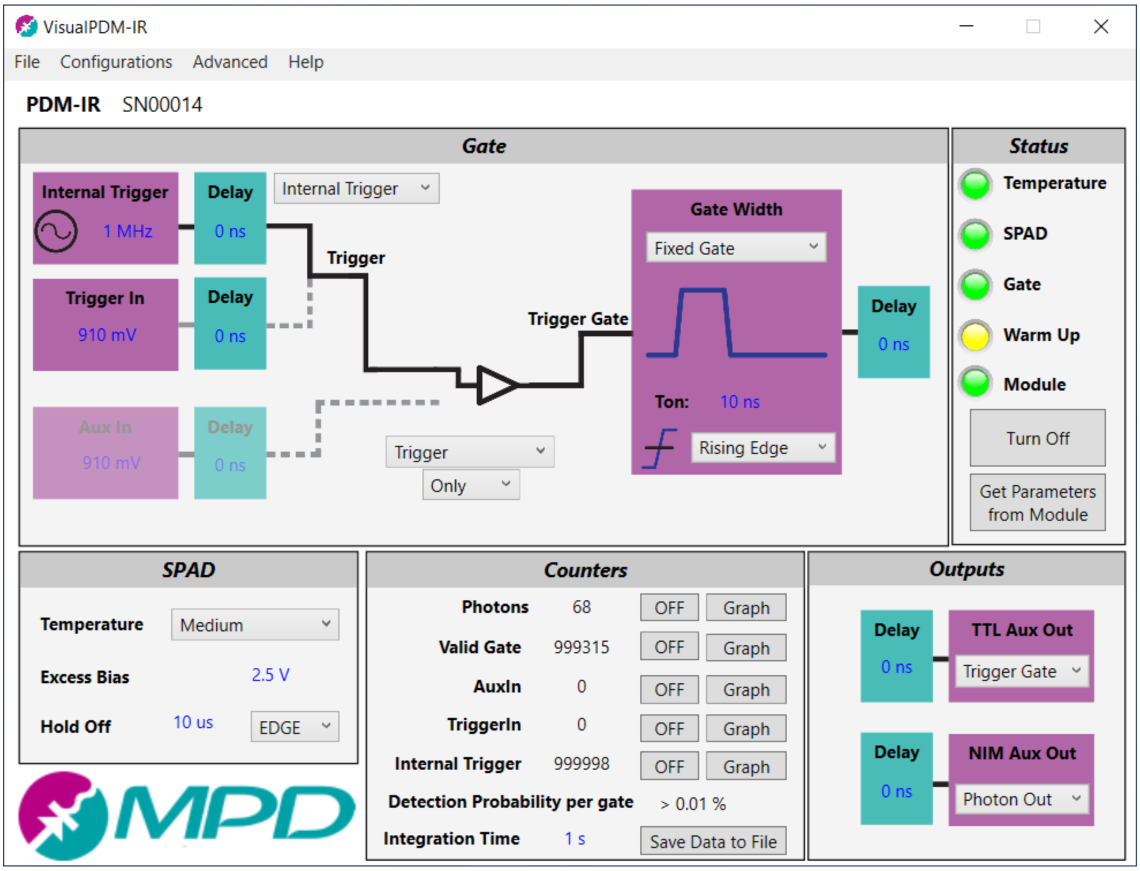


Figure 18. Screenshot of the main window of the graphical user interface.

5.2.1 Main Window: Trigger and Gate Section

This panel manages the trigger and gate settings as described in PDM-IR Trigger Section and PDM-IR Gate Section. Figure 19 shows a screenshot of the section and Table 12 explains the meaning of each control.

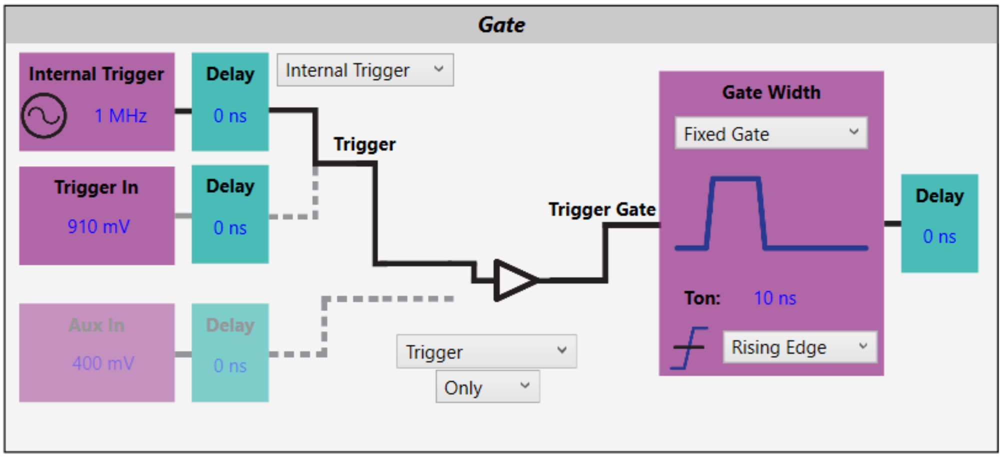
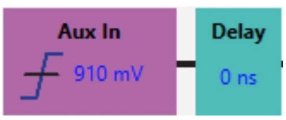
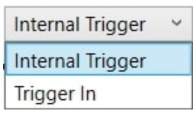
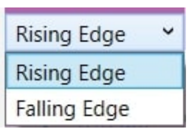
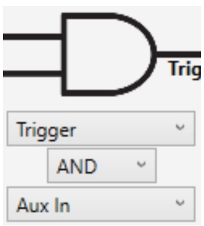
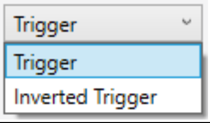
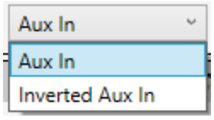
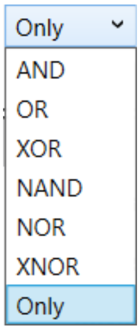
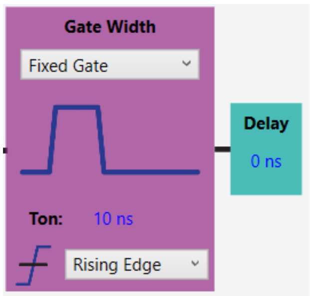
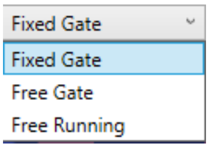


Figure 19. Trigger and Gate Section of the VisualPDM-IR Main Window.

Table 12. Trigger and Gate Section explained.

	**Internal Trigger Settings**: these two fields set the frequency ($freq_{IN}$) and the Delay of INTERNAL TRIGGER ($\delta_{INT\_TRIGGER}$).
	**Trigger In Settings**: these two fields set the threshold level (V_{TH_IN}) and the Delay of TRIGGER IN ($\delta_{TRIGGER\_IN}$).
	**Aux In Settings**: these two fields set the significant edge (Edge Selection List), the threshold level (V_{TH_AUX}) and the delay of AUX IN ($\delta_{TRIGGER\_AUX}$). These controls are disabled when Logic Function gate List is equal to "Only" (see below).
	**Trigger Selection List**: let the user to choose TRIGGER between INTERNAL TRIGGER and TRIGGER IN.
	**Edge Selection List**: selection list used in both the Aux In settings box and the Trigger In settings box for choosing the rising or the falling edge of the input signal
	**Logic Function Settings**. Set the logic function (Logic Function gate List) between TRIGGER (Logic Function Input1 list) and AUX IN (Logic Function Input2 List) to generate TRIGGER GATE.

	**Logic Function Input1 list**. Allows to invert or not the TRIGGER input before sending it to the logic gate.
	**Logic Function Input2 List**. Allows to invert or not the AUX IN input before sending it to the logic gate. This field is not visible and enabled when the logic port is set to "Only" (see below).
	**Logic Function gate List**: selects which logic gate will be used to combine TRIGGER with AUX IN. "Only" means TRIGGER ONLY and thus TRIGGER will be identical to TRIGGER GATE and sent directly to the gate generation section.
	**Gate Width Settings**: these fields allows to select the gate mode (see PDM-IR Gate Section), the T_{ON} width, the triggering edge and the delay of the EFFECTIVE GATE ($\delta_{EFFECTIVE\_GATE}$). The T_{ON} and trigger edge fields are of course visible only in case of gate mode with fixed gated width.
	**Gate Mode List**: allows to choose the Gate Mode operation. It can be gate mode with fixed gate width (Fixed Gate), gate mode with free-gate operation (Free Gate), or Free running mode (Free running).

5.2.2 *Main Window: SPAD Section*

This panel manages the SPAD settings (Figure 20) like Temperature (see paragraph 4.3.1), Excess Bias (see paragraph 4.3.2) and Hold Off time (see paragraph 4.3.3). Each control is explained in Table 13.

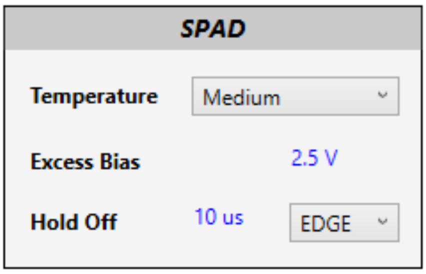
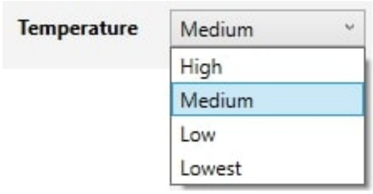
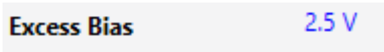


Figure 20. SPAD Section of the VisualPDM-IR Main Windows.

Table 13. SPAD Section controls explained

	**Temperature**: Allows to change the SPAD working temperature through a selection list. See paragraph 4.3.1 for more information
	**Excess Bias**: set the SPAD Excess Bias Voltage (V_{EX})
	**Hold Off**: set the Hold Off time (t_{HO}) of the SPAD. LEVEL and EDGE select the synchronism with the gate. See paragraph 4.2 for details.

5.2.3 <u>*Main Window: Output Section*</u>

The panel in Figure 21 manages the outputs (see paragraph 4.5). Each control is explained in Table 14.

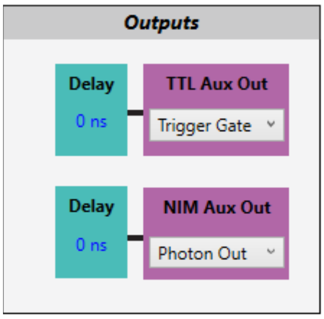
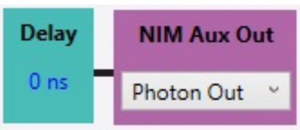
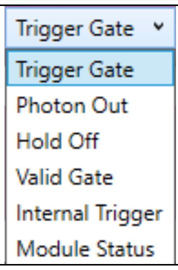


Figure 21. Output Section of the VisualPDM-IR Main Windows.

Table 14. Output Section controls explained.

	**TTL AUX OUT**: these two fields set the desired TTL output signal chosen from the Out Signal List and the delay introduced in the output path (δ_{TTL_AUX}).
	**NIM AUX OUT**: these two fields set the desired NIM output signal chosen from Out Signal List and the delay introduced in the output path (δ_{NIM_AUX}).
	**Out Signal List**: list of signals that can be routed to the output connectors.

5.2.4 Main Window: Status Section

This panel shows the actual module status (Figure 22). Each control is explained in Table 15.

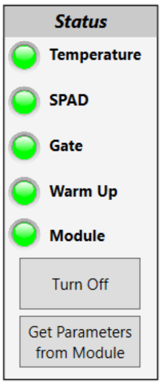


Figure 22. Status Section of the VisualPDM-IR Main Windows.

Table 15. Status Section controls explained.

Temperature	**Temperature Status**: Indicates the SPAD temperature status. *Dark Green LED* means the SPAD temperature controller is working properly but it isn't cooling the SPAD. *Yellow LED* indicates that the controller is changing the SPAD's temperature. *Light Green LED* means that the SPAD temperature is set correctly. *Red LED* indicates an error of the temperature controller.
SPAD	**SPAD Status**: Indicates the SPAD bias status. *Dark Green LED* means that the SPAD is properly working but it is biased below the breakdown voltage and thus it is not able to detect photons. *Yellow LED* indicates that the SPAD bias voltage is currently changing. *Light Green LED* means that the SPAD is correctly biased and ready to detect photons according to the GATE settings. *Red LED* indicates that an error occurred during the SPAD bias voltage setting.
Gate	**Gate Status**: Indicates the gate mode status. *Dark Green LED* denotes that the Gate is off. *Yellow LED* denotes that PDM-IR is updating GATE settings. *Light Green LED* means that the gate is ON.
Warm Up	**Gate Status**: Indicates the gate mode status. *Dark Green LED* denotes that the PDM-IR is warmed. *Yellow LED* denotes that PDM-IR is warming up.
Module	**Module Status**: Indicates the module status. *Light Green LED* means that the module has no errors. *Red LED* indicates that there is at least an error on the module. The Red LED is associated with a pop-up message indicating the error.
Turn Off	**Turn Off**: Disables the SPAD. This button is visible only *when the SPAD is ON*.
Turn On	**Turn ON**: Enables the SPAD. This button is visible only *when the SPAD is OFF*.
Get Parameters from Module	**Get Parameters from Module**: this button reads from PDM-IR all module parameters and thus synchronizes the SW interface with actual module settings. The SW interface is always synchronized with the module, anyway, when the module is powered OFF/ON without closing the SW a resynchronization is needed.

5.2.5 Main Window: Counter Section

PDM-IR has five internal counters that can be enabled or disabled. Once enabled, it is possible to see each actual counter value or its variation in time through graph displayed in a satellite window. The integration time is user settable and common for all counters. The counters data can saved on a csv file (comma-separated values). This counter panel is shown in Figure 23 while controls are explained in Table 16.

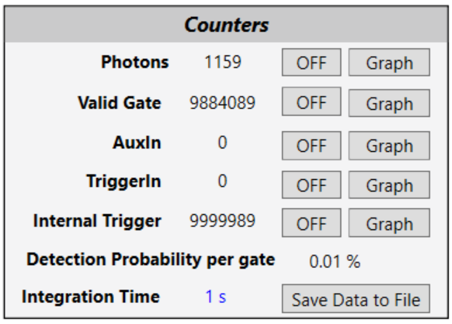


Figure 23. Counter Section of the VisualPDM-IR Main Windows.

Table 16. Counter Section controls explained

Photons 1431 Valid Gate 986589 AuxIn 0 TriggerIn 0 Internal Trigger 999998	**Counter Values**: displays the last values read from each counter
Valid Gate 95321 OFF Graph	**OFF button**: it's visible when the counter is enabled. The OFF button disables the counter. **Graph button:** opens the time chart of the relative counter (see 5.2.6).
AuxIn --- ON Graph	**ON button**: it's visible when the counter is disabled. The ON button enables the counter and the Graph button. **Graph button:** it is disabled and greyed when the counter is disabled.
Detection Probability per gate 0.01 %	**Detection probability per gate**: displays the probability to detect a photon in a gate window. It's calculated as photon counts divided by valid gate counts.
Integration Time 1 s	**Integration time:** sets and shows the integration time of the displayed values.
Save Data to File Stop data saving...	**Save data:** save counter values to csv file. The file is updated every integration time. the integration time can't be modified in the data are stored in a file. "Save data to File" starts the data acquisition after choosing the name path. "Stop data saving…" stops the data acquisition

5.2.6 Counter Window

This satellite window shows the counter graph for evaluating the counts vs time (Figure 24) and display the counter data values and the relative controls. Each control is explained in Table 17.

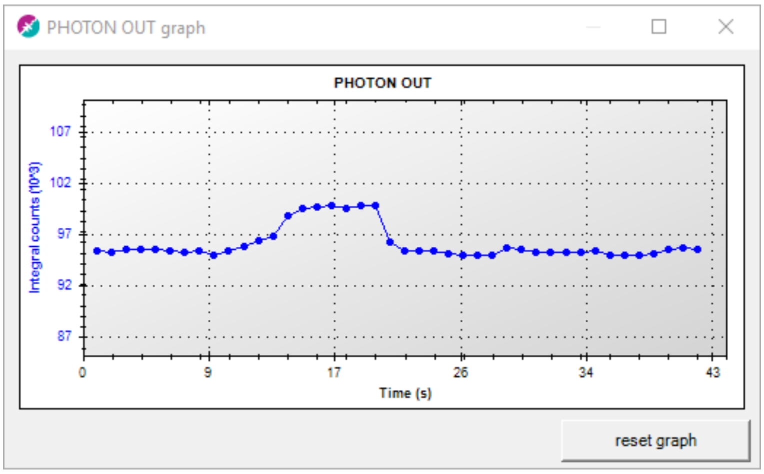
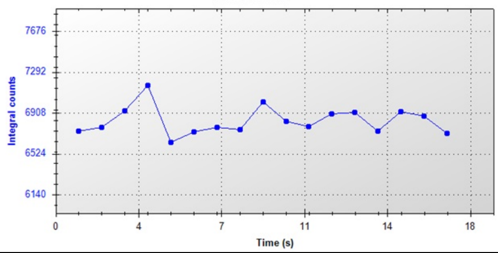


Figure 24. Counter Graph of the VisualPDM-IR. Satellite Window.

Table 17. Counter Graph controls explained.

PHOTON OUT	**Counter type:** indicates the counter type
	**Graph Area**: display the counts trace
reset graph	**Reset Graph**: clean Graph Area.

5.2.7 Module Selection Window

In case of multiple PDM-IRs connected at the same PC, the software offers the possibility to control all of them, by means of the pop-up widow shown in Figure 25. In this figure the list of all detected PDM-IR modules is indicated, allowing the user to choose or change the controlled PDM-IR by the Serial Number. Actual active module is also shown by the SW interface in the top left corner as shown in Figure 18. The pop-up window is immediately shown at SW start-up, in case of detection of more than one PDM-IR connected to the PC. The user can also switch between modules by opening the pop-up window by means of the run-time menu File → Open Module (see paragraph 5.2.11). Every time a new module is selected pressing the OK button, the software gets the actual configuration from the module.

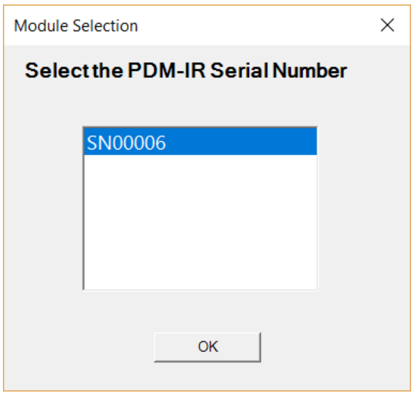


Figure 25. Pop-up window for the module selection.

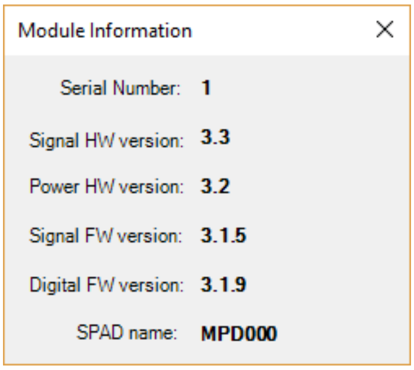


Figure 26. Pop-up for PDM-IR module information.

5.2.8 *Module Info Window*

With the software interface it is possible to read the module hardware and revision versions for diagnostic purposes, for example when contacting MPD for support. This pop-up (shown in Figure 26) can be opened by pressing the "Show PDM-IR Module Info" button in the "Advanced" menu.

5.2.9 *Configurations Window*

A complete set of parameters that fully configures a PDM-IR is called a "Configuration". With the VisualPDM-IR it is possible to save multiple configurations and load them whenever a specific one is needed for a particular application or experimental set-up. In order to see which configurations are stored and to load them, the "*Load Configuration*" menu item, in the "Configurations" run time menu, should be pressed. Upon pressing, the pop-up window shown in Figure 27 is opened. The module can store up to 10 configurations, with three of them preconfigured by MPD. While the latter are not erasable, all other user's configuration can be deleted by selecting them and then pressing the "Delete Configuration" button. Of course, in order to upload a configuration in the module, it must be selected in the Configurations List and then the "Load

Configuration" button should be pressed. Whenever a configuration is selected, the load configuration window will also preview it in the dedicated window-panel as shown in Figure 27. Finally, with the same window, it is possible to set a configuration as power up configuration, i.e. the one that will be loaded when the PDM-IR is powered on without the need to be attached to a PC. This operation is performed by pressing the "Save Configuration as Startup" button. It is also worth noting that the configurations are stored inside the module and thus can be accessed anywhere, even when a module is moved from one lab to another and thus connected to different PCs.

5.2.10Save configuration Window

In order to save a configuration, the menu item "Configurations → Save Configuration" should be selected. This action will open the window shown in Figure 28. In order to save a configuration, first the desired configuration name must be written in the dedicated text box, then the "Save" button should be pressed. The name will be useful for identifying it in the configurations list. Please be aware that the SW does not verify if the configuration name has been already used or not. Instead, by pressing the "Cancel" button, the window will be closed with no saved configuration.

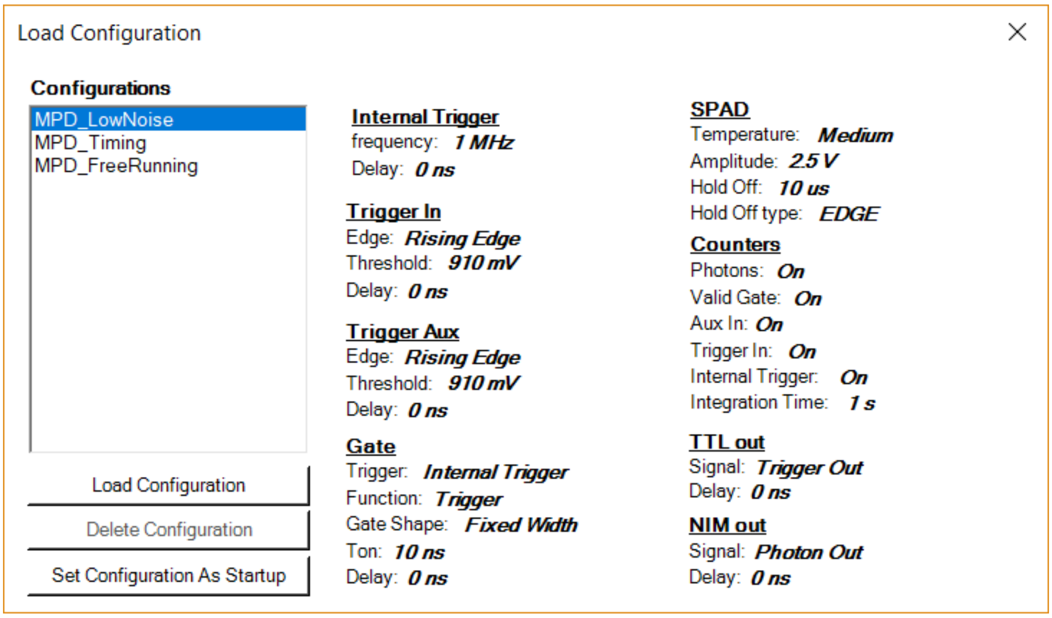


Figure 27. Pop-up window for module configurations.

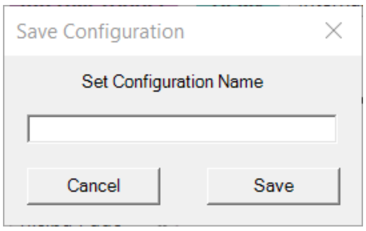


Figure 28. Pop-up for save the current configuration.

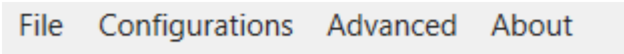


Figure 29. Runtime menu.

5.2.11 RunTime Menu

The VisualPDM-IR has the runtime menu shown in Figure 29. The functions unlocked by the various menu items have been already described in the previous paragraphs and are summarized again in Table 18.

Table 18. Runtime menu controls explained.

File → Open Module	Allows to change the PDM-IR that is controlled by the SW when more than one module are attached to the same PC. By pressing the menu item, the module selection window, shown in paragraph 0, will appear.
File → Exit	Closes the software and the communication with the module.
Configurations → Load Configuration	Opens the configurations window (see paragraph 5.2.9).
Configurations → Save Configuration	Allows to save the current configuration in the module, and to assign a name to it (see paragraph 5.2.10).
Advanced → Show PDM-IR Module Info	Shows the hardware and firmware version of the module (see paragraph 5.2.8).
About	Shows the software version.

6 Setup Examples

In this chapter, some measurement examples are briefly discussed.

6.1 Basic setups

6.1.1 Photon Counting setup

Photon-counting is the simplest type of measurement performable with the module and Figure 30shows a possible example of the experimental setup. It consists of a continuous wave laser that produces photons at 980 nm, properly attenuated, and a sample that absorbs photons and re-emits in the near infrared part of the electromagnetic spectrum. These photons, properly collected, are sent to the SPAD detector.

As the laser in this example produces a continuous wave, the photons emitted from the sample will be asynchronous respect to any trigger, including the module internal one. Thus, for detecting these photons, the PDM-IR can be used either in free running mode or in gated mode. The internal counter associated to the NIM OUT (Photons) can also be conveniently used without the use of an external one. In free running mode the measurement is straightforward (see paragraph 2 for a description the various modes of operation and paragraph 4.2.3 specifically for free running): as the SPAD is immediately turned on following each avalanche triggering, all photons impinging on the detector, apart those coming during the hold-off time, are detected. Thus, supposing N_{imp} the number of impinging photons on a SPAD active area during an integration time T, N_{count} the photons counted by the detector in the same integration time, and considering the PDE, N_{count} is equal to N_{imp} reduced by the PDE and multiplied by the ratio between the actual integration time and the set one T:

$$N_{count} = N_{imp} \cdot PDE \cdot \frac{T - N_{count} \cdot T_{HO}}{T} = N_{imp} \cdot PDE \cdot (1 - N_{count} \frac{T_{HO}}{T}) = \frac{PDE \cdot N_{imp}}{1 + PDE \cdot N_{imp} \cdot \frac{T_{HO}}{T}}$$

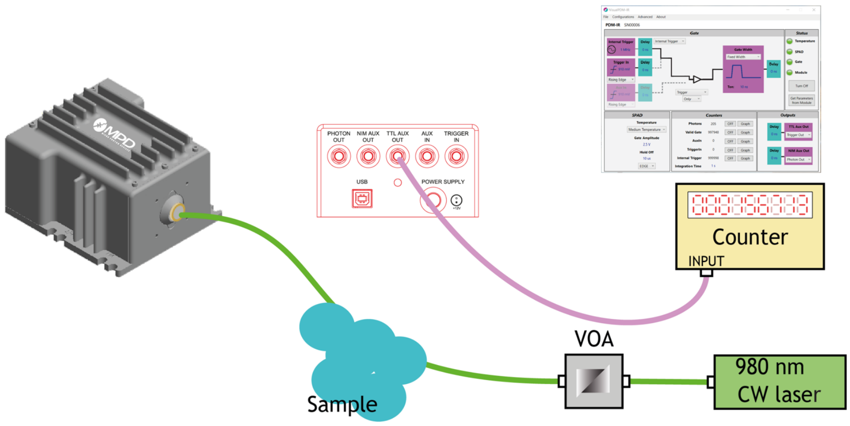


Figure 30. Simple setup for a photon-counting measure (green: optical signals, pink: electric signals).

By expressing N_{imp} as a function of N_{count} one obtains also:

$$N_{imp} = \frac{1}{PDE} * \frac{N_{counted}}{1 - N_{counted} * \frac{T_{HO}}{T}}$$

or, by dividing both sides of the equation by the integration time we obtained the very simple equation:

$$CR_{imp} = \frac{N_{imp}}{T} = \frac{1}{PDE} * \frac{N_{counted}/_{T}}{1 - N_{counted} * \frac{T_{HO}}{T}} = \frac{1}{PDE} \cdot \frac{CR_{count}}{1 - CR_{count} \cdot T_{HO}}$$

So, in order to calculate the impinging count rate, the user just need to measure the module count rate (CR_{count}) and to correct for both the detection efficiency (calculated at the experiment wavelength) and the HOLD-OFF.

In case, the user wants to perform the same measurement in gated mode, the PDM-IR should be set in gated mode with internal trigger and Fixed gate width operation (see paragraph 2 for a description the various modes of operation and paragraph 4.2.1 specifically for Gated-Mode with Fixed-Gate-Width). Even in this case the internal counter “Photons” can be conveniently used. As already explained in paragraph 2, due to the combined effect of the hold-off and the fact that the SPAD is enabled only during gate-ON windows of width T_{ON} and period TP, the calculation of the impinging photon flux CR_{imp} is a bit more complex and equal to:

$$CR_{imp} \cong \frac{1}{PDE} \cdot \frac{CR_{count}}{1 - CR_{count} \cdot T_{HO}} \cdot \frac{TP}{T_{ON}} \quad for \quad \frac{CR_{count} \cdot TP}{1 - CR_{count} \cdot T_{HO}} \ll 1$$

From the above equation it turns also out that:

$$CR_{count} \cong \frac{PDE \cdot \frac{T_{ON}}{TP} \cdot CR_{imp}}{1 + PDE \cdot \frac{T_{ON}}{TP} \cdot CR_{imp} \cdot T_{HO}}$$

Which means that detecting asynchronous photons with a gated mode configuration always reduces the efficiency in counting photons of the quantity T_{ON}/TP, which is simply the duty-cycle D at which the SPAD is switched on/off. In other words, a gated mode module running asynchronous respect to the signal behaves as a free-running with a lower efficiency and SNR and thus, in this case, the free running mode should be chosen (Poisson noise is the square root of signal and thus a lower count rate means a higher noise). This is true if the hold-off is long enough so that the afterpulsing is low, otherwise it might be more advantageous for the SNR, the gated mode which would reduce the number of avalanches and thus the afterpulsing.

Of course, if the laser would have been a pulsed one, using a gated mode operation would have been much more advantageous. In this case, indeed, the detector is turned on only when signal and noise are present and turned off when only noise can be measured. As consequence, the signal is detected with PDE efficiency, while noise is reduced by the duty-cycle factor. Additionally, as the hold off is typically microsecond long, the module has a longer ON time, compared to a free running operation, as it is not switched off by noise during the OFF part of the gate, further improving the SNR.

6.1.2 Photon Timing setup

Another typical setup in which the PDM-IR is used is a photon-timing one, illustrated in Figure 31. This setup can be adopted for measurement of fast waveforms of repetitive optical pulses. The technique is commonly known as Time Correlated Single Photon Timing (TCSPC). This setup consists of a pulsed laser source which excites a fluorescent sample that reemits photons with an exponential decay. In this example the module is still internally triggered. Additionally, in this case, the NIM AUX OUT has been set to output the INTERNAL TRIGGER and has been connected to the trigger-in input of the laser. In this way, the laser is triggered by the PDM-IR module. The trigger-out signal of the laser is then used, as START of a TCSPC system. The STOP signal to the TCSPC system is given by the PHOTON OUT of the PDM-IR module. It is worth noting that in this example the INTERNAL TRIGGER, used to synchronize the laser, has been routed to the NIM AUX OUT as we supposed to use a laser which can accept negative pulses and that it is triggered on the negative edge, like with PicoQuant semiconductor lasers. In other cases, the TTL AUX out might have been better suited. As a general rule, when connecting instruments, it is very important to verify the voltage levels and the polarity of all the involved signals and to attenuate/invert them if necessary in order to comply with the inputs' absolute maximum ratings.

In order to ensure that the photons, emitted by the sample, impinge on the detector when the gate is enabled, it is necessary to take particular care to signal propagation delays inside the cables and in the instruments, included the PDM-IR (see paragraph 4.7 for the actual numbers).

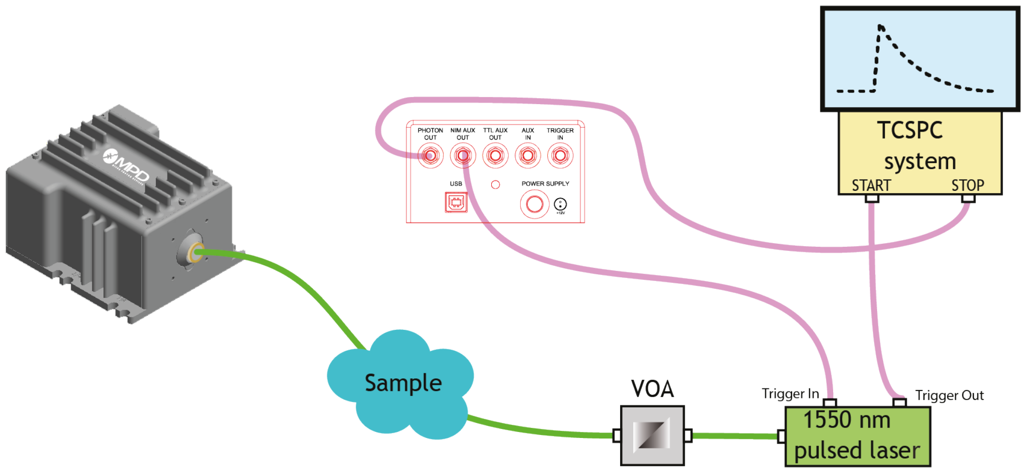


Figure 31. Simple setup for a photon-timing measure (green: optical signals, pink: electric signals).

In this case all the equations used in the previous example are still valid and can be used in order to calculate the actual counting rate of the detector. Anyway, the TCSPC technique is normally adopted in order to correctly reconstruct the shape of the temporal response of fast pulses or fast fluorescence decays (like in our example) by accurately measuring photon arrival times and not simply measuring the number of counts in a period of time.

When using the TCSPC technique it is very important to avoid the pile-up effect. This is normally achieved by attenuating the laser light so that only the 5% (or 1%) of the emitted fluorescence pulses are detected by the sensor, i.e. module count rate should be smaller than 5% (1%) of the laser repetition rate. However, as we are now in gate mode it is very important to correctly calculate the count rate. Additionally the equations described in paragraph 2 are not valid as module duty cycle D should not be considered: since the Gate window is synchronized with the laser, all laser photons reach the detector always when the latter it is on. As a consequence, the correction due to the gate mode does not apply because for the laser pulses the SPAD behaves as if operated in free running. Only the correction for the hold-off time must be implemented. In addition, we will consider negligible the effect of the DCR and of the afterpulsing: the minor error that is committed is conservative in calculating the correct counting-rate for avoiding the pile-up effect.

The condition to be satisfied is thus that the module count rate CR_{count} should be smaller than 5% (or 1%) of the laser pulses effectively shined on the detector, i.e. those emitted when the SPAD was not in HOLD-OFF:

$$CR_{count} < 5\% \cdot f_{EFF} = 5\% \cdot (f_{laser} - CR_{count} \cdot \frac{T_{HO}}{D_{laser}}) = 5\% \cdot (f_{laser} - f_{laser} \cdot CR_{count} \cdot T_{HO})$$

and thus, simplifying:

$$\frac{CR}{1 - CR \cdot T_{HO}} < 5\ \% \cdot f_{laser}$$

where $D_{laser} = 1/f_{laser}$, T_{HO} is the hold-off time and CR is the actual module counting rate as measured at a counter.

6.2 Advanced setups

6.2.1 Cross correlation setup with an external synchronization

In many cases, cross-correlation measurements have low photon rate, that's why, optimizing the setup to collect as many photons as possible is the main goal. This paragraph analyzes the measurement setup and a PDM-IR configuration to get the best results. A cross correlation setup is commonly composed by two PDM-IR because there are at least 2 optical channels to detect and, as described in paragraph 2, it's important to enable the SPADs only when the photons impinge on the detector. Figure 32 shows a case where the synchronism signal is provided by the pulsed laser and the PDM-IRs can be enabled only for the required time to collect the photons. Anyway, due to the long hold off time (tens of microseconds), there is a significant probability that when the signal photons arrive at the detectors, one of the two is disabled due to a previous avalanche. This reduces the SNR because a correlated count can’t be detected and, whenever the enabled SPAD is triggered, a distortion in the measurement is also created (the other SPAD did not count because the expected photon did not arrive or was not seen for the PDE < 1 but because it was OFF). Even if this distortion could be corrected, the effect of such event would anyway be a longer measurement time. The best solution is thus to enable both SPADs only if they both can detect photons.

A proposed solution is here described step by step:

1. Set the PDM-IRs to work in fixed gate width mode (see 4.2.1) and with the GATE generated by TRIGGER IN.
2. Connect the LASER TRIGGER OUT to the TRIGGER IN of each PDM-IR by means of a wideband 50/50 power splitter (the voltage levels at the outputs are the half of the input levels); set the correct edge and threshold settings of the TRIGGER IN input.
3. Set the correct TRIGGER IN delay so that detectors are enabled when the photons arrive
4. Set the correct T_{ON} width so that it is longer than the correlation curve to be acquired.
5. For each module use the second input connector (AUX IN) to get the HOLD OFF status of the other module: set the TTL AUX OUT as HOLD OFF, set the AUX IN threshold voltage around 1 V with rising edge trigger edge, connect the TTL AUX OUT of each module to the AUX IN of the other module. AUX IN delay and TTL AUX OUT delay should be set to 0 ns to minimize the time of synchronization of the two modules.
6. Set the AND as the Logic Function between TRIGGER IN and NOT AUX IN: the SPAD of each module is enabled only when the other module isn’t in hold off.
7. Use the PHOTON OUT outputs as correlator system inputs.

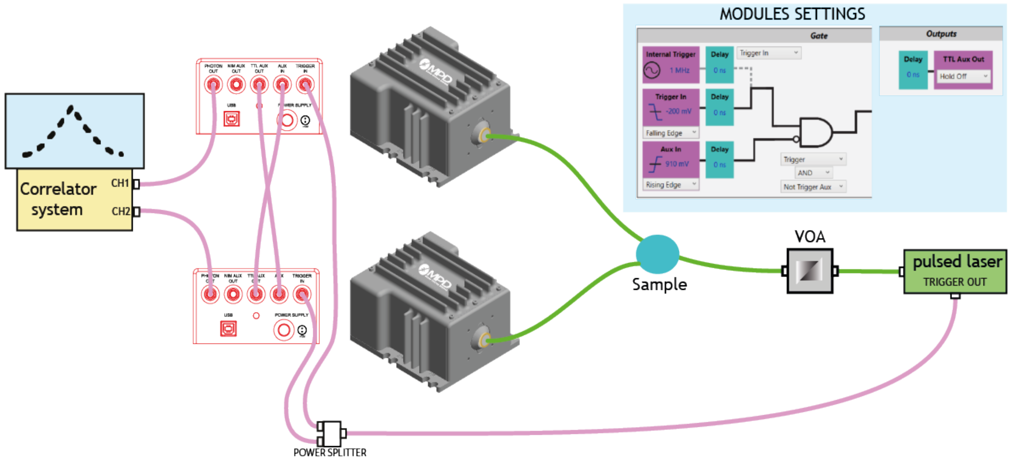


Figure 32. Example setup for cross correlation measurements with an external sync.

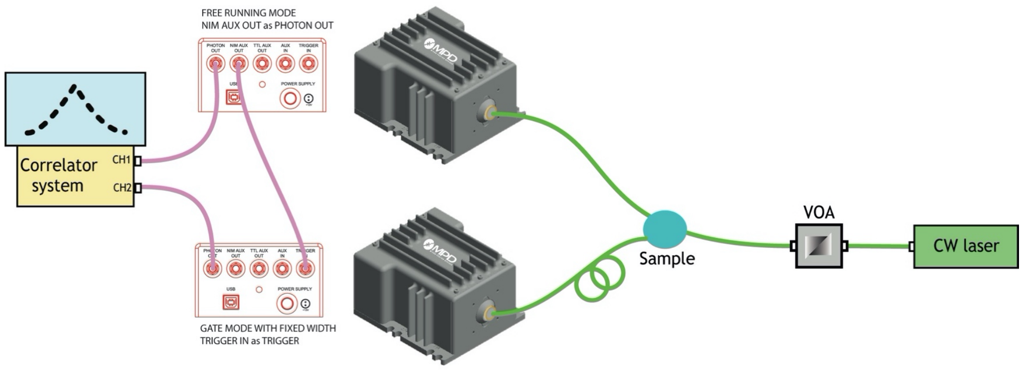


Figure 33. Example setup for cross correlation measurements without external sync.

6.2.2 Cross correlation setup without an external synchronization

Whenever photons are emitted totally asynchronously, previous set-up cannot be used. For example, if the sample emits photons stimulated by a CW laser, there is no possibility to sync the PDM-IR with the photon emission for calculating the cross-correlation. In order to overcome this limitation, the simplest setup is composed by both PDM-IR in free running mode. Anyway, this setup doesn't optimize the measurements because one of the two detectors could be in hold off while the other detects the correlated photon. As result, the SNR is drastically reduced due to the high InGaAs/InP DCR.

This paragraph describes an alternative solution, shown in Figure 33, that allows to collect better results. With this configuration one module is set to work in free running mode in order to collect as much asynchronous photons as possible. The other PDM-IR is set to work in gated mode with fixed gate width and his own TRIGGER IN is connected to the NIM AUX OUT of the other module. Setting the NIM AUX OUT of the free-running module as PHOTON OUT, the gated SPAD is enabled ONLY every time the first module detects a photon. Finally, in order to make this setup working two other settings must be ensured:

1. Since there is a fixed delay from the instant a photon is detect by the free-running PDM-IR to the instant the gate is opened on the second PDM-IR (due to modules internal delays, see paragraph 4.7, and the cable used to connect the two modules), photons arriving at the gated PDM-IR must be delayed by making longer the optical path from the sample to the gated PDM-IR. In case of an experimental set-up using optical fibers, this can be easily archived by using longer optical fiber patches.
2. In order to be sure that the gated PDM-IR can be gated-on whenever the trigger arrives from the free-running module, the gated SPAD MUST NOT BE in HOLD-OFF. Setting the hold off time of the free-running module longer than the sum of gate-width and hold-off time of the gated module, will allow the above condition to be met.

6.2.3 Long Decay Measurement

Short Decay measurements up to hundreds of nanoseconds can be measured in gated mode with fixed gate width without any particular issue (see paragraph 6.1.2): for ensuring that the photons emitted by the sample impinge on the detector when the gate has been enabled, it is necessary to take particular care to signal propagation delays inside cables, optic fibers and instruments, including the PDM-IR. This information is easily obtained by reading the instruments respective user manuals. In this way the gated mode photon counter behaves as if it would be a free-running module: the detector is always ON when the photons arrive.

Longer decays, in the range of microseconds, have usually maximum laser repetition rates in the order of few hundreds of kHz or lower, in order to avoid aliasing effects. With such sources, setting up a TCSPC might not be easy and the condition on detection rate, for avoiding the pile-up effect, could impair the measurement acquisition time. Indeed, the easiest way to measure such decay would be the use of the module in free running mode. In this way, the condition to avoid the pile-up effect would be that the module count-rate, corrected for the hold-off, should be smaller than 5% (1%). Anyway, in this situation with laser frequencies of 100kHz or smaller the condition becomes 5kc/s, 1kc/s or smaller and modules dark counting rates could be already in the same order of magnitude or larger. It would thus seem that in case of a module with DCR = 5kc/s and an experiment with 100kHz of f_{LASER}, a TCSPC measurement would not be possible. This is not the case. Let's start from the known formula and let's also separate the contributions of the signal CR_{signal} from the noise CR_{noise} (noise can be DCR only or DCR plus an uncorrelated background light); let's also name CR_{total} the sum of CR_{signal} and CR_{noise}, which is the count rate with no corrections that can be simply seen by attaching the PDM-IR PHOTON OUT to a counter (or by using the internal "Photons" counter):

$$\frac{CR_{signal} + CR_{noise}}{1 - (CR_{signal} + CR_{noise}) \cdot T_{HO}} = \frac{CR_{signal}}{1 - CR_{total} \cdot T_{HO}} + \frac{CR_{noise}}{1 - CR_{total} \cdot T_{HO}} < 5\% \cdot f_{LASER}$$

Now we have two terms in the above equation, one with the contribution of the signal and the other one with the contribution of the noise. As seen, both noise and signal contribute to the pile-up effect, anyway only the counts inside the TCSPC Region Of Interest (ROI) should be considered. Specifically, it important to consider only noise distortion over the same time window of the signal and not outside the signal limits. Indeed, background noise distortion comes with a non-flat curve in a TCSPC measurement (not easily removable thus) and it is important that only the part within the signal time limits is distorted less than 5%. Supposing to select a ROI large enough to contain the whole signal, and thus the signal contribution to the pile-up effect is considered unmodified, but not much longer than the signal duration, so that noise contribution can be reduced by the ratio between the ROI and the laser period $D_{LASER} = 1/f_{LASER}$, the equation above becomes:

$$\frac{CR_{signal}}{1 - CR_{total} \cdot T_{HO}} + \frac{CR_{noise}}{1 - CR_{total} \cdot T_{HO}} \cdot \frac{ROI}{D_{laser}} < 5\% \cdot f_{LASER}$$

For example, supposing f_{LASER} = 100 kHz, T_{HO} = 10µs, CR_{noise} = 5kc/s and ROI = 20µs, one obtains that CR_{signal} = 3571 c/s. Since CR_{noise} is the count rate that can be read by a counter (like the internal Photons), without any correction for the HOLD OFF and since CR_{signal} is the signal count rate, i.e. the T_{HO}-uncorrected count rate one could ideally measure if detector noise could be “switched off”, the above result would mean that when module PHOTON OUT count rate is 3571 c/s + 5000 c/s = 8571 c/s, than the PDM-IR is at the 5% TCSPC limit. It is also worth pointing out that in MPD datasheets all the DCR values are corrected by the HOLD-OFF. As a consequence, if a test report states that, a specific PDM-IR with a specific configuration has DCR = 2k/s, it means that when connecting this module to a counter and by using the stated configuration, the read count rate CR_{noise} would be:

$$2000\frac{c}{s} = \frac{CR_{noise}}{1 - CR_{noise} \cdot T_{HO}} \Longrightarrow CR_{noise} = \frac{2000\frac{c}{s}}{1 + 2000\frac{c}{s} \cdot 10\mu s} = 1960{,}78\ c/s$$

Summarizing, it is possible to measure a microsecond decay signal with a free running PDM-IR provided the above equation is used for calculating the pile up effect.

A better solution, but a bit more difficult to implement, would be to acquire only few “slices” of the decay curve, as sampling points (see Figure 34) and recreate the full decay curve fitting these points. This could be achieved by using the PDM-IR in gated mode with a hold-off time longer than the ROI, so that only one pulse per decay, as in the equivalent free running mode, would be counted. Anyway, in this case and respect to the free running mode, both signal and noise would be reduced by the same factor D, where D is the gated mode duty cycle, calculated as ratio between the slice on time T_{ON} (i.e. the PDM-IR gate on time) and the repetition period T (i.e. PDM-IR gate frequency). Anyway, in this case the laser could be increased for the signal only of the same factor D or actually even a bit more as with a lower noise it is possible to push even further the signal before reaching the 5% (1%) pile up limit. Additionally, by reducing the number of dark counts, the detector is, on average, ON and ready to detect signal-photons for a longer time as the hold-off time caused by noise is also reduced. Finally, it is also worth noting that any distortion due to the long hold-off is kept negligible because of the low count rate with respect to the laser frequency.

Summarizing, while with a free running module, a decay measurement is the simplest, with a gated mode module used to sample the decay, it is possible to increase the SNR even more that the duty D at the expense of having a curve sampled and not “continuous”.

In order to perform this measurement using the setup proposed in Figure 35 follow the instructions:

1. Set the PDM-IR trigger as INTERNAL TRIGGER and set the internal frequency between 10 to 100 times higher than the desired laser trigger frequency (the laser trigger frequency is application dependent)
2. Set the NIM AUX OUT as TRIGGER GATE and connect it to the MPD Picosecond Delayer input. The PSD, in this application, is used as divider, in order trigger the laser at the desired frequency, i.e. 10 to 100 times less than the module gate frequency.
3. Acquire the raw data of the histogram by setting correctly the TCSPC system parameters.
4. Elaborate the histogram with a custom-made program or Matlab function.

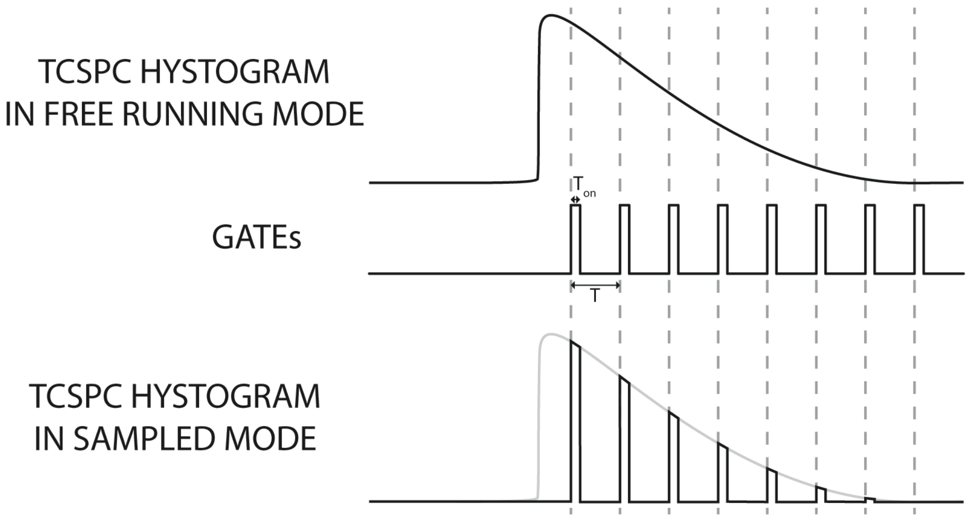


Figure 34. Free running mode vs Sampled mode of a long decay curve.

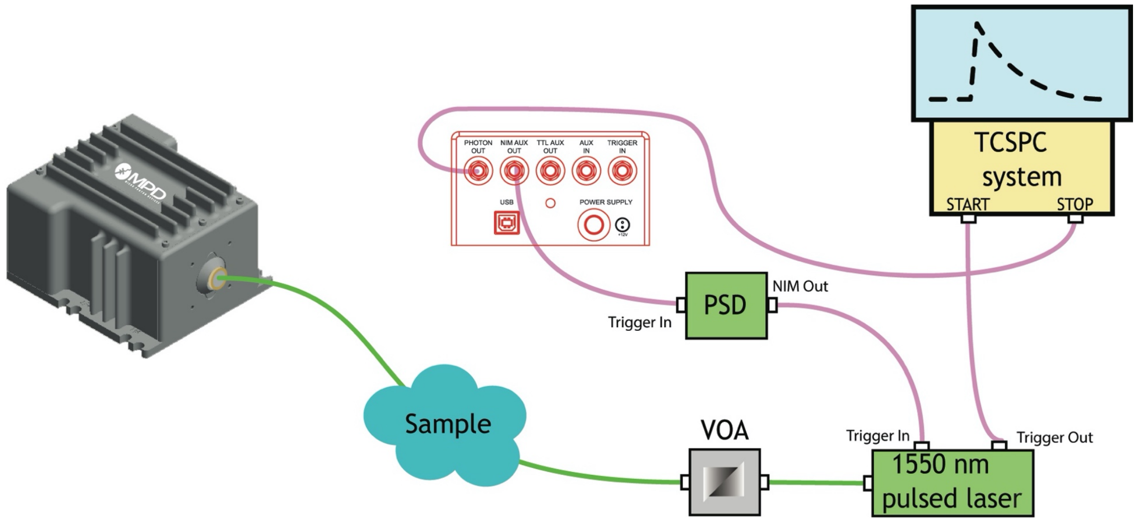


Figure 35. Example setup for lon decay measurements.

7 System requirements

- USB 2.0 interface
- Host computer (minimum requirements)
    - 1 GHz processor and 512 MB of RAM
- Supported operating systems
    - VisualPDM-IR
        - Microsoft Windows XP, Vista, 7, 8,10, 32 or 64 bit versions
    - SDK
        - Microsoft Windows XP, Vista, 7, 8, 10, 32 or 64 bit versions
        - Linux Ubuntu 12.04 LTS, Fedora Core 15 or compatible distributions, 32 or 64 bit versions. Different distributions should work, but were not tested.
        - Mac OS X 10.7.5 and above

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