



TCSPC Technology Used in SPAD (APD) Test System

This document is used to describe the basic principles, and **SIMTRUM**'s solution for the Single Photon Avalanche Diode (SPAD) or Avalanche Photon Diodes (APD) testing

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Content Index

- [SPAD\(APD\) Test Objectives and principle](#)
- [TCSPC Testing Solution for bear chip SPAD \(APD\)](#)
- [TCSPC Testing Solution for packaged SPAD \(APD\) TO46 or T08](#)

Test Objectives and principle

This test system is suitable for the Geiger working mode of SPAD, using gated quenching technology, quasi-single photon source and counting principle, it can measure SPAD's avalanche voltage value V_a , dark count rate DCR, single photon detection efficiency SPDE, after the pulse probability P_a and the time jitter TJ, it can be used as a SPAD (APD) mass production testing platform and a SPAD (APD) performance testing platform.

The test objectives and basic principles of the test system are briefly described as follows:

- 1) Single Photon Detection Efficiency (SPDE) of SPAD: According to the average number of photons per pulse μ for a given laser (generally $\mu = 0.1$), measure the probability of dark counts generated by each gated pulse of SPAD P_d , and the probability of related counts generated by each light pulse P_e , then the single-photon detection efficiency SPDE can be calculated as:

$$SPDE = \frac{1}{\mu} \ln \frac{1 - P_d}{1 - P_e}$$

Generally, the dark counting probability P_d is much less than 1, and when $\mu = 0.1$, the optical pulse correlation counting probability P_e is also much less than 1, then $SPDE$ can be approximated as:

$$SPDE = \frac{1}{\mu} P_e$$

- 2) Normalized dark count rate DCR of SPAD: Since SPAD works in a gated mode with a certain gate width τ , for uniformity, the dark count rate of SPD P_d , that is, the probability of dark counts generated by each gate pulse, Converted to the dark count rate in the Geiger mode of SPAD, that is, the normalized dark count rate R_d :

$$R_d = P_d / \tau$$

3) Pulse probability after SPAD P_a : This parameter generally needs to specify the gating operating frequency, which characterizes the total probability of subsequent avalanche pulses caused by the incidence of effective photons caused by the capture and release of photoelectrons by internal defects in SPAD at a specific gating operating frequency^[1]. Let the total count of SPD in unit time be R_s , the dark count in unit time be R_d , and the unit time count related to the photon arrival time is R_e , if the gate frequency is F_g , the incident photon pulse frequency is F_p , then the post-pulse probability P_a is calculated as:

$$P_a = \frac{\frac{F_g}{F_g - F_p} (R_s - R_e) - R_d}{R_e - \frac{F_p}{F_g} R_d}$$

4) SPAD time jitter: The output jitter of the avalanche signal relative to the optical pulse synchronization signal can be measured in the gated mode. This parameter represents the fluctuation of the SPAD single-photon avalanche relaxation time. Usually, a time-correlated single-photon counter is used to count the effective avalanche signal. FWHM of time histogram $t_{jitter,FWHM}$, or use a high bandwidth oscilloscope to count effective snow $t_{jitter,RMS}$ of the time offset of the avalanche signal relative to the optical pulse synchronization signal. For the time jitter of the nearly Gaussian distribution, there are generally:

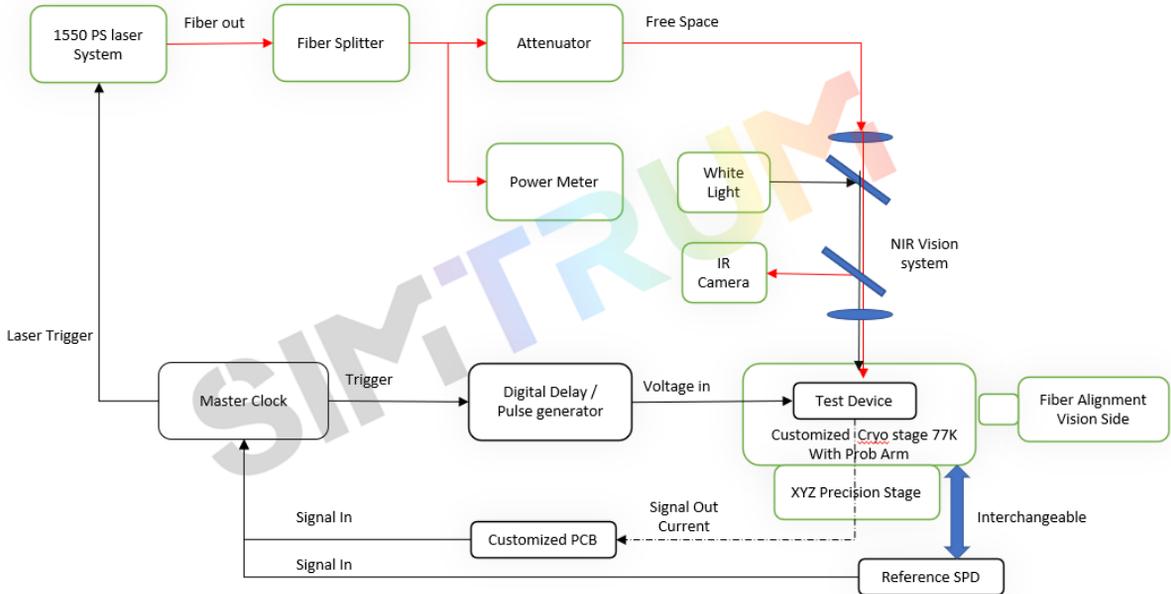
$$t_{jitter,FWHM} = 2.35 * t_{jitter,RMS}$$

^[1] If SPAD is in Geiger mode, this parameter usually needs to be given with a certain dead time parameter, but this system uses gated control mode, and its default dead time is the length of one pulse period, so the dead time is generally the minimum value here. If necessary, the setting of dead time can be increased by parameters.

TCSPC Testing Solution for Bear Chip SPAD (APD)

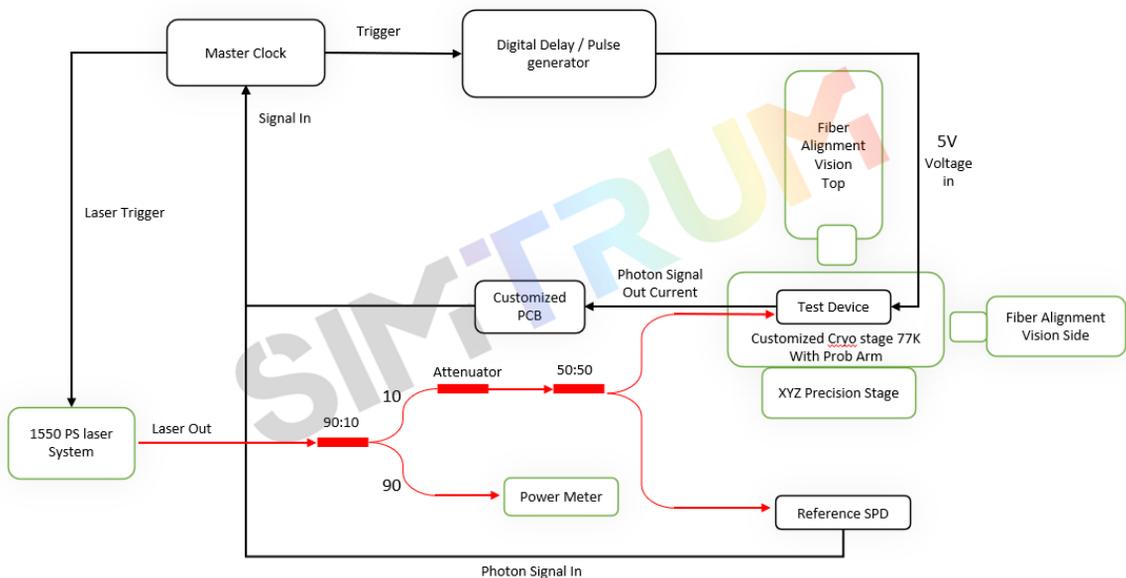
Free-space Bear Chip SPAD TCSPC Testing System

This is composed of a picosecond pulse laser instrument QLD-301, free-space optical setup, Digital delay pulse generator for gate control, Cryo-stage system for 70K cooling, Optical power meter, reference SPD and a set of TCSPC master clock is required.



Fiber-based Bear Chip SPAD TCSPC Testing System

This is composed of a picosecond pulse laser instrument QLD-301, fiber optical setup, Digital delay pulse generator for gate control, Customized fiber Cryo-stage system for 70K cooling, Optical power meter, reference SPD and a set of TCSPC master clock is required.



The QLD-301 picosecond pulsed laser includes:

- Signal generator module (Clock source distribution): It can receive an external reference clock or use an internal clock source to generate a synchronized laser pulse trigger clock and APD gated clock with adjustable relative delay. In general, the frequency of the APD gate control clock is an integer multiple of the laser trigger clock, and the system provides options of 2 times, 5 times, 10 times, 20 times, 50 times, and 100 times;
- Picosecond pulsed laser (Pulsed Laser): It can generate laser pulses synchronized with the trigger clock at the same frequency, the pulse width is less than 50ps, and the extinction ratio is greater than 40dB. In addition, the laser synchronization clock generated by it is used as the input signal of the counting module;
- Optical power monitoring and attenuation control module (ATT): control the attenuation of the laser pulse to attenuate it to the level of single photon and ensure the stability of the pulse power through high-sensitivity optical power monitoring.

Master Clock

- 4 Channel input and 4 Channel output, Channel number customizable, high resolution up to 13ps bin width, timing jitter per channel 5.7ps.
- Maximum input voltage range -3 to 3V (customizable)

High Voltage Pulse generator

- 4 pulse output and 8 delay outputs, less than 25ps rms jitter, trigger rate up to 10mhz.
- High voltage trigger signals up to 10V. this is important for SPAD testing device.
- Raise and fall time up to 55ps.

Reference SPD detector

- Wavelength coverage 900 - 1700nm (able to change to VIS range for different application)
- Timing resolution 150ps Dark count rate 20% at 3Khz, 1us to 100us adjustable deadtime

Free space NIR optical system with Cryo-stage

- Um level laser spot size on testing sample, with coaxial NIR vision system for optical alignment
- 2 adjust probe arm for electronics signal testing, Cryo-stage temperature able to reach -77K (LN2)



Appendix A. Calibration method for the average number of photons per pulse of laser pulses

Before the performance test of the SPAD, it is necessary to accurately calibrate the average number of photons per pulse of the laser. The calibration process has the following methods:

1. Indirect power calibration method: Calculate the required output power according to the optical pulse repetition frequency and the average number of photons per pulse^[2], and then calculate the required external attenuation value according to the output power of the QLD-301 (displayed value or measured value), hand-held optical power. The attenuation value of the external attenuator is calibrated so that the final output power reaches a predetermined value. The main problem of this method is that it requires additional calibration of the value of the external attenuator, which is complicated in operation.
2. Direct power calibration method: This method uses a high-precision instrument-type optical power meter, such as Keysight 81634B, whose nominal measurement accuracy can reach -110dBm, but the actual measurement accuracy is about -100dBm. If the average number of photons per pulse is required to be 0.1, this method only It can be used to calibrate optical pulses with repetition rate above 10MHz. The main problem of this method is its limited scope of application and high cost.
3. Single-photon counting direct calibration method: This method uses a single-photon detector whose detection efficiency has been calibrated for direct single-photon counting. Because the detection efficiency is known, the average number of photons per pulse can be directly calculated through the counting rate and the optical pulse frequency^[3]. The method has fast calibration speed, good repeatability, a wide application range, simple and efficient.

The characteristics of the above three schemes are compared in the following table:

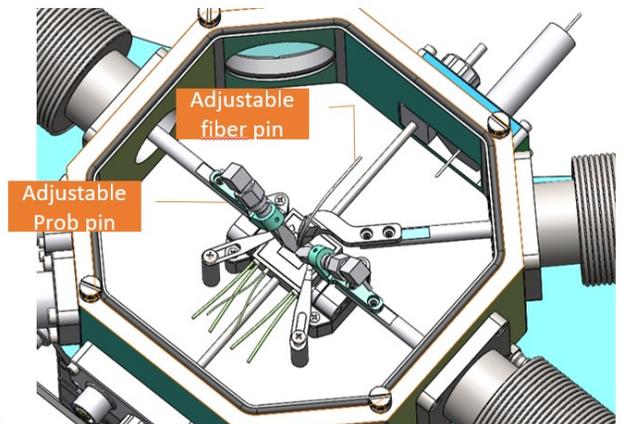
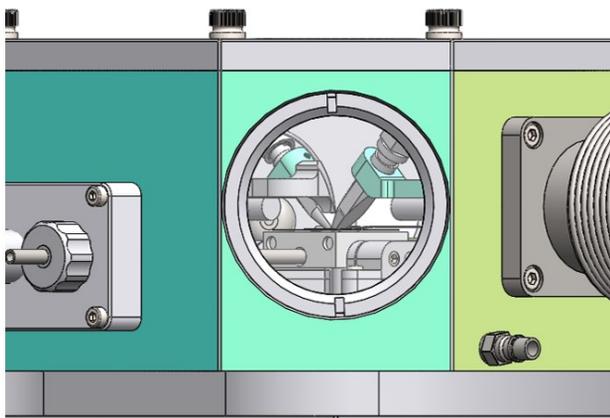
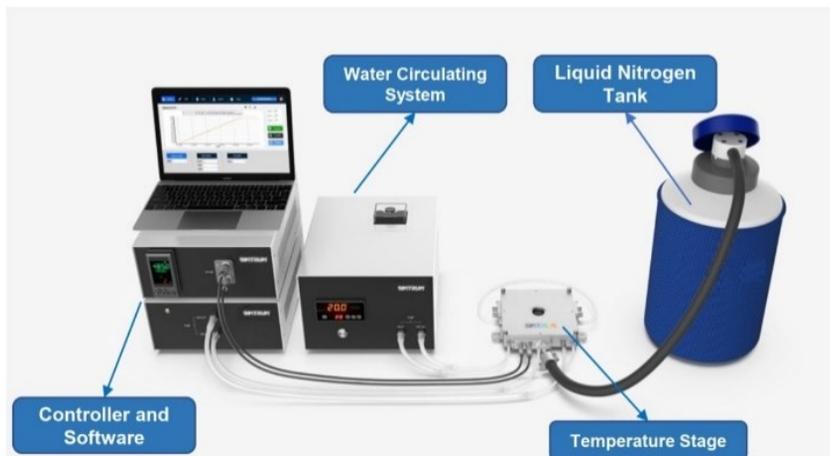
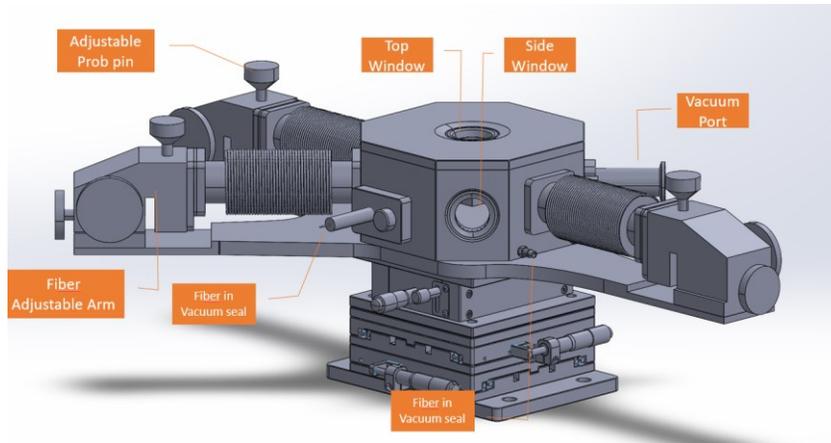
Calibration Method	Complexity	Cost	Measurement Accuracy
Indirect Power Calibration Method	high	Low	Low
Direct Power Calibration Method	Low	high	middle
Single Photon Counting Direct Calibration Method	Low	middle	high

^[2] For example, the average power of the 1550nm optical pulse at 1MHz with $\mu=0.1$ is -108.92dBm

^[3] If the single-photon detection efficiency SPDE=10%, the count rate of the 1MHz optical pulse with $\mu=0.1$ is 10KHz.

Customized fiber Cryo-stage system for 70K cooling

- Customized fiber inserts into the testing chamber , with 85 degrees optical output angle.
- Top and side view visible zoom vision system for fiber alignment.
- 2 adjust probe arm for electronics signal testing, Cryo-stage temperature able to reach -77K (LN2).



Performance

The specific performance index parameters are shown in the table below.

Parameter	Specification	Remark
Laser QLD-301-1550		
Laser Repetition Rate	1MHz~1.25GHz	For SPAD test systems, the recommended laser pulse frequency range is 1MHz~100MHz, internal trigger
Minimum Pulse Width	< 50ps, FWHM	
Time Jitter	< 20ps,RMS	Measured relative to SYNC OUT
Pulse Extinction Ratio	>40dB	
Center Wavelength	1550nm	
Internal Trigger Delay Range	0~1000ns	SPAD test system uses internal triggering to generate an AUX OUT synchronous clock for Gated trigger clock for SPAD
Delay Adjustment Accuracy	10ps	
Optical Power Monitoring Sensitivity	<-75dBm	The internal PD sensitivity is better than -75dBm , and the external 35dB solid attenuation can support the minimum power detection range of -110dBm , which meets the optical power detection requirements of $\mu = 0.1$ at 1MHz .
Internally Adjustable Attenuation Range	0~40dB	
Auxiliary Clock Output Frequency	1MHz~1.25GHz	As the SPAD gate trigger clock frequency, it can be set to an integer multiple of the laser pulse repetition frequency
Gated Generation Module NPG-1H20		
Gated External Trigger Frequency	Covers 0.1~100MHz	
Gate Width	Covering 0.5~2ns , 10ps/step	Encoder adjustment
Gate Amplitude	Covers 4~6.4V , better than 100mV/step	Encoder adjustment
Pulse Polarity	Positive Pulse	
Rise Time	<120ps	20%~80%
Fall Time	<150ps	20%~80%
Digital Delay / Pulse Generator		
Channels	4 or 8 output	
Jitters	<25ps	
Voltage Output	Up to 30V	High voltage gate signal
Raise & Fall Time	100 ps	
Single Photon Detector		
Wavelength Range	900-1700	
Deadtime Range	0.1-100	
Dark Count Rate	20% @3Khz	
Timing Resolution	150ps	
Optical Fibre Coupling	MMF62.5 or Free space	
Master Clock		
Channel	4input and 4 output	
Bin Width	13ps	
Time Jitter	8ps	
Count Rate	1Ghz	

TCSPC Testing Solution for packaged SPAD (APD) TO46 or TO8

The Packaged SPAD test system is composed of picosecond pulse laser instrument **QLD-301**, gate control generation module **NPG-1H20**, test main control module ATE-301 and test chassis (including TO46 water-cooled refrigeration unit). In addition, a set of **TCSPC instruments is required**. Used to test post-pulse and time jitter. Among them, QLD-301 is a picosecond pulse laser with a built-in signal source, which can generate electrical and optical pulses with adjustable delay (currently an independent instrument, which can be upgraded to a module later as a chassis board);

NPG-1H20 can generate gated pulse signal with adjustable amplitude and pulse width; ATE-301 part contains APD correlation mode Blocks (high-pressure generation, refrigeration and temperature control, two-channel discrimination counter); the test case includes TO46 refrigeration and signal extraction unit, chassis backplane, etc., of which TO46 refrigeration and signal extraction unit includes: water cooling radiator, thermal insulation structure, TEC Refrigeration unit, spike noise suppression and signal extraction circuit, TO-46 fixture and signal interface, etc. The system composition and principle-block diagram are shown in the following figure:

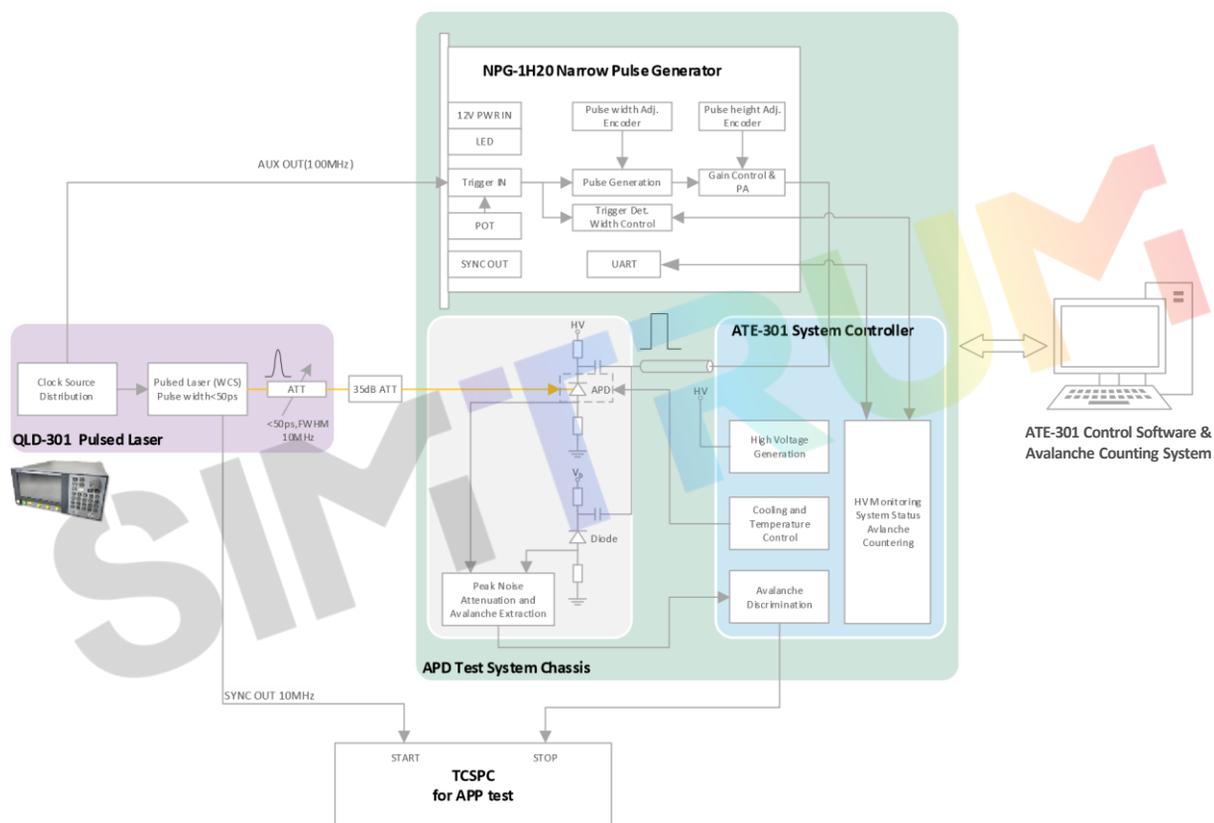


Figure 1 System composition and principle-block diagram of SPAD test platform

The QLD-301 picosecond pulsed laser includes:

- Signal generator module (Clock source distribution): It can receive an external reference clock or use an internal clock source to generate a synchronized laser pulse trigger clock and APD gated clock with adjustable relative delay. In general, the frequency of the APD gate control clock is an integer multiple of the laser trigger clock, and the system provides options of 2 times, 5 times, 10 times, 20 times, 50 times, and 100 times;
- Picosecond pulsed laser (Pulsed Laser): It can generate laser pulses synchronized with the trigger clock at the same frequency, the pulse width is less than 50ps, and the extinction ratio is greater than 40dB. In addition, the laser synchronization clock generated by it is used as the input signal of the counting module;
- Optical power monitoring and attenuation control module (ATT): control the attenuation of the laser pulse to attenuate it to the level of single photon and ensure the stability of the pulse power through high-sensitivity optical power monitoring.

NPG-1H20 gate control generation module mainly includes:

- Trigger input and monitoring unit, the trigger frequency covers 0.1~100MHz, compatible with any level trigger input;
- The gate control amplitude is adjustable, the adjustment range covers 4~6.4V, better than 100mV/step, the encoder adjustment;
- The gate width is adjustable, the adjustment range covers 0.5~2ns, 10ps/step, encoder adjustment.

ATE-301 test main control module mainly includes:

- SPAD related modules: including High Voltage Generation, Cooling and Temperature Control and other modules; the system is based on the gated quenching method, so that the SPAD works in the gated mode, and in this mode, the detection efficiency, normalized dark count rate and post-pulse probability of the SPAD are tested;
- Dual channel counter module (dual channel counter): used to count the avalanche count value and can be upgraded to a coincidence counting module later, and automatically measure the post-pulse probability by synchronizing the clock with the laser to automatically find the peak and count the coincidence function.

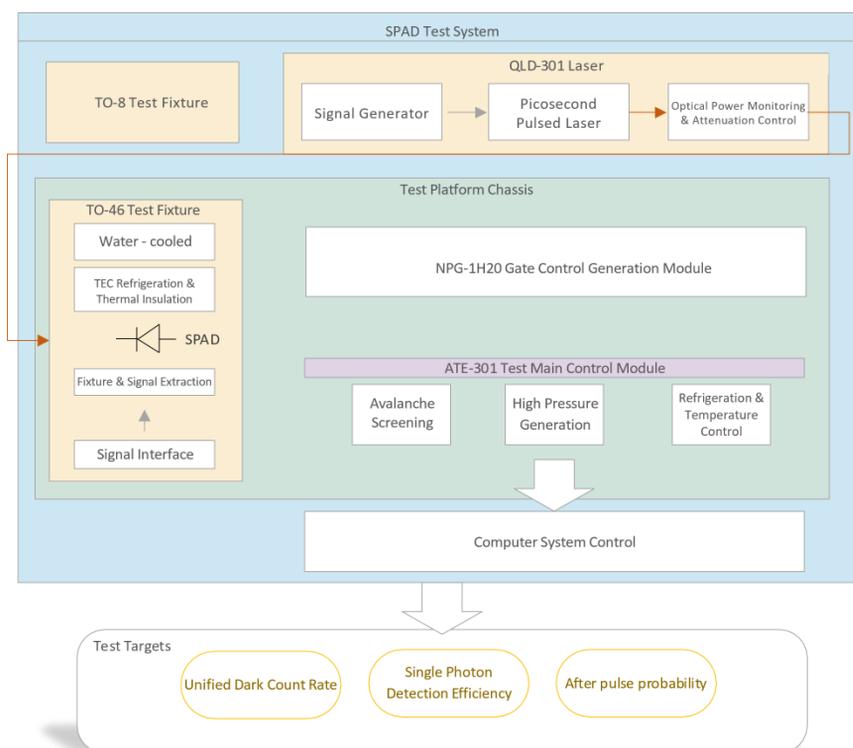


Figure 2 Schematic Diagram of the Composition of the Scheme

TO-46 test fixture mainly has:

- Water-cooled TEC refrigeration and thermal insulation structure: using industrial grade three-stage refrigeration sheet, combined with water-cooling heat dissipation technology, temperature control of $\leq -60^{\circ}\text{C}$ can be achieved at room temperature of 20°C , meeting the low temperature requirements of SPAD; Minimize heat radiation and heat convection.
- SPAD fixture and analog front end: It adopts unique pure copper heat conduction fixture and high-speed balanced differential technology to support SPAD in TO-46 package (maximum outer diameter 6mm, package structure is shown in Appendix 1), and the structure is easy to replace; High suppression of spike noise, which can effectively extract the avalanche signal of SPAD;
- Signal interface: including optical pigtail exit, RF coaxial and DB9 interface, which are used to transmit single-photon signal, gated input signal, avalanche output signal and high voltage and temperature control interface of the system host respectively.

Remark:

1. Due to the individual differences of SPADs, the effects of pin reflection on the noise suppression of each SPAD are quite different. The current scheme adopts an adjustable mechanism design. On the basis of retaining the pins, adjusting the contact position of the pin connector can adjust the noise to Minimum, which improves the accuracy of the DCR test.
2. he TO-8 package also needs to design a fixture and a heat dissipation structure and design a gate-based balance cancellation circuit for the extraction of avalanche signals. This part was not considered before, and the manpower and cost may exceed the budget cost.

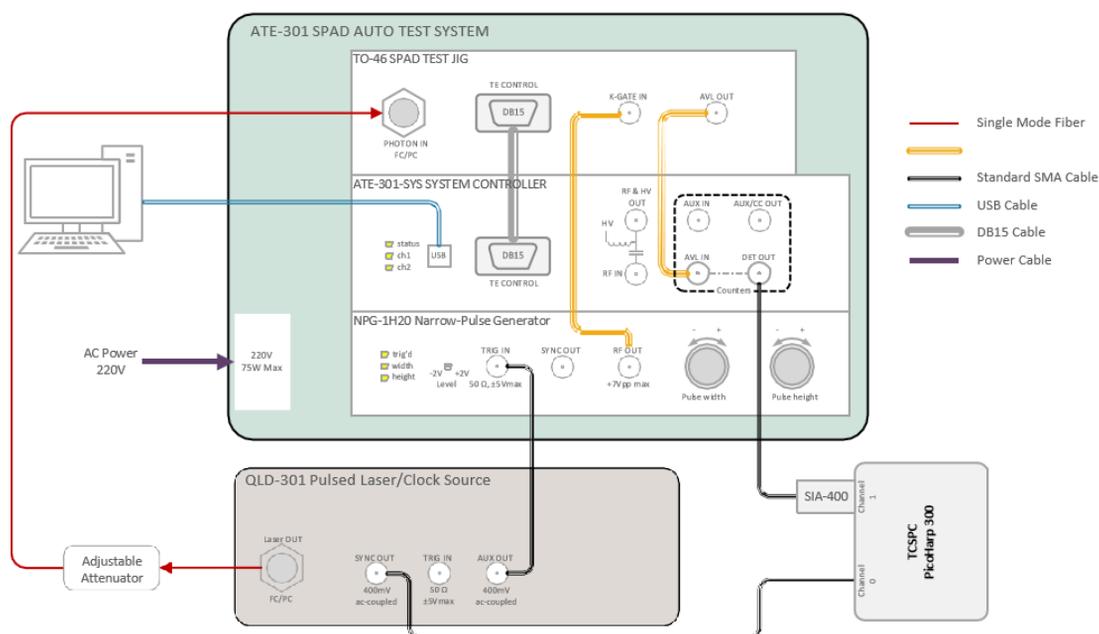
Performance

The specific performance index parameters are shown in the table below.

Parameter	Specification	Remark
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Time Jitter	< 20ps,RMS	Measured Relative to SYNC OUT
Pulse Extinction Ratio	>40dB	
Center Wavelength	1550nm	
Internal Trigger Delay Range	0~1000ns	SPAD test system uses internal triggering to generate an AUX OUT synchronous clock for Gated trigger clock for SPAD
Delay Adjustment Accuracy	10ps	
Optical Power Monitoring Sensitivity	< -75dBm	The internal PD sensitivity is better than -75dBm , and the external 35dB solid attenuation can support the minimum power detection range of -110dBm , which meets the optical power detection requirements of $\mu = 0.1$ at 1MHz .
Internally Adjustable Attenuation Range	0~40dB	
Auxiliary Clock Output Frequency	1MHz~1.25GHz	As the SPAD gate trigger clock frequency, it can be set to an integer multiple of the laser pulse repetition frequency
Gated Generation Module NPG-1H20		
Gated External Trigger Frequency	Covers 0.1~100MHz	
Gate Width	Covering 0.5~2ns , 10ps/step	Encoder adjustment
Gate Amplitude	Covers 4~6.4V , better than 100mV/step	Encoder adjustment
Pulse Polarity	positive pulse	
Rise Time	<120ps	20%~80%
Fall Time	<150ps	20%~80%
Test the Main Control Module ATE-301-SYS		
High Pressure Range	50~90V adjustable	
High Voltage Regulation Resolution	0.01V	
Limit Cooling Temperature	-60 °C	In the laboratory room temperature 20 °C environment, and maintain good ventilation
Temperature Control Accuracy	± 0.1 °C	
Cooling Time	<8min	
TCSPC post-pulse test (currently using TCSPC for post-pulse test, subsequent functions can be upgraded and embedded in ATE-301-SYS)		

System Connection Block Diagram

The figure below is the system connection block diagram, in which the ATE-301-SYS, NPG-1S20 and TO-46 test fixtures are all located on the test platform chassis, which can reduce the system size and facilitate operation.



ATE-301 TO-46 SPAD test system connection block diagram

Applicable APD Package TO-46 Example Diagram

