VIZIBLE SPECTRUM SINGLE PHOTON DETECTION MODULE

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Abstract: *Experiments using entangled photons and their applications require the detection of extremely weak light beams: the incoming photons arrive to the detector one at a time.*

Visible spectrum single photon detection is a challenging problem because the photon energy can produce only one electron-hole pair and such a signal is less than the sum of the intrinsic noise of the semiconductor detector and the associated electronics. Nevertheless, a free electron can initiate an avalanche discharge within an avalanche photodiode (APD), reversely polarized at a value slightly higher than its breakdown voltage. The discharge quenching and the restoration of the APD voltage are necessary to enable another photon detection.

The module we are talking about is using both the passive quenching – to limit the discharge current to small enough values, considered safe – and the active quenching – to increase the upper margin of the measuring range to values as high as 1,… 1.5 mega pulses per second.

Some major technical problems we have dealt with, to create a single photon detection module are presented:

- APD equivalent dynamic resistor evaluation;

- shielding against background light;

- controlling the APD working temperature.

A selected list of module measured characteristics concludes the presentation.

Keywords: *single photon counting*

1. INTRODUCTION

Because of their small size, high quantum efficiency, large spectrum range, capability to detect VIS single photons, the APDs are the most used transducers in entangled-photons experiments.

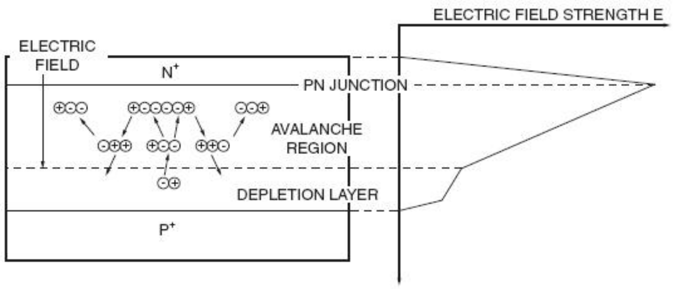
This paper reports experimental results useful to determine some characteristics not specified in the data sheet of the APD, like: actual breakdown voltage, dynamic resistor, quenching current.

The passive and active quenching principle schemata are shortly reviewed in order to explain the functional scheme of the single photon detecting module. Relying on it, application software architecture is presented.

To assure a negative working temperature for the APDs, constructive requirements for thermal and optical subassemblies interfere. An example to solve the problems is given. A selected list of module measured characteristics concludes the presentation.

2. AVALANCHE CURRENT GENERATION

Let's consider the incident photon generates the e-h pair within the depletion layer (see Fig. 1) of a reversely biased avalanche photodiode (APD). The electron gets in the avalanche region, where the electric field strength is high enough to accelerate it at a drift speed higher than 10^7 cm/s [1]. So, it produces new e-h pairs when colliding with the crystal lattice. The process repeats many times and an avalanche current results.



a) b)

Fig.1. a) A section through an APD; b) Internal electric field strength versus deep. (Taken form [1]).

3. PASIVE QUENCHING CIRCUIT

When the APD is connected in a circuit like depicted in Fig. 2, the avalanche current produces a sudden increase of the input voltage, v_i, and, simultaneously, a decrease of the voltage v_1 to a value called breakdown voltage (VB). Actual waveforms can be seen in Fig. 3.

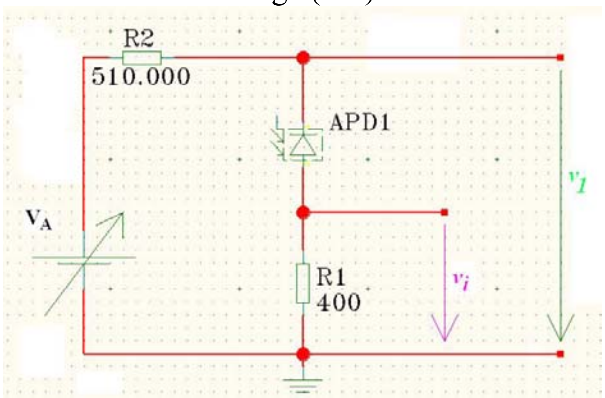


Fig. 2. The scheme of the passive quenching single photon detector.

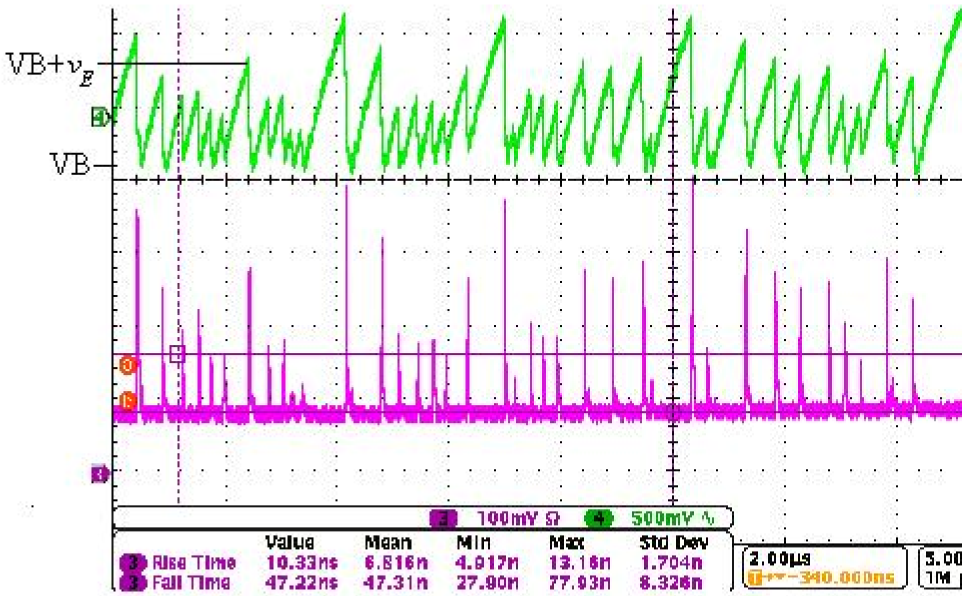


Fig. 3. Waveforms: ch. 3 – input voltage v_i; ch. 4 – APD cathode voltage v_1.

The v_1 waveform (see Fig. 3, ch. 4), suggests a charging capacitor, C_d, through a resistor, R2+R1 in Fig.2, from the level VB to a random level VB + v_E followed by its discharge through a much smaller resistor, r_d . That is why the APD equivalent circuit is the one drawn in Fig. 4. The switch K1, normally off, is turned on when the avalanche arises and keeps on conducting as long as the current is greater than a value called quenching current, I_q [2] .

The diode capacitance is specified in the component data sheet. Also, a breakdown voltage is presented but defined as follows: the reverse continuous voltage across the diode when its current equals 100 μA [3]. This value is slightly greater than the VB noted in Fig. 3. The dynamic resistor, r_d, and the quenching current have to be experimentally determined. The rise time of the input pulse (see Fig. 5) and the electric scheme (see Fig. 2) offer the necessary data to estimate the r_d value; we have found r_d = 250,…,500 ohm for the APD type S9074.

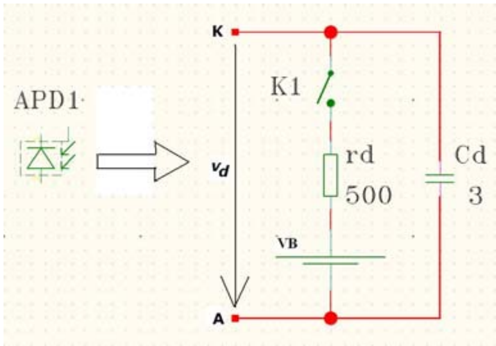


Fig. 4. The APD equivalent scheme.(Taken from [2]).

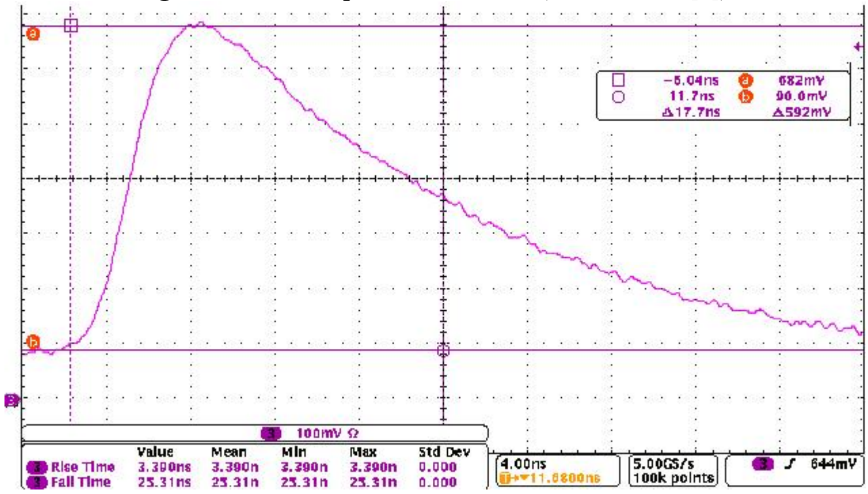


Fig. 5. An input pulse – rise time measuring.

By reducing the ballast resistor value (R2 in Fig. 2), all the other parameters being kept constant, one can obtain waveforms like in Fig.6. They reveal both the existence of higher pulses than in Fig. 3 and the quenching absence (the quenching is marked by the beginning of the recharging period) for times in μs range.

Such a situation allows the measurement of the current intensity through R2, between pulses; this is a slightly over estimated value (62,…,65 μA in our case) of the I_q, because the avalanche process goes down by itself only when the interpulses current intensity becomes smaller than the quenching value [4].

Let us assume we have determined the minimum ballast resistor value, $R2_{opt}$, to assure immediate quenching. Now, connect the capacitor $C1 \geq C_d$ (see Fig. 7): significantly higher input pulses are obtained because the excess voltage is divided by R1 and r_d not R1 and $(R2 + r_d)$ as previously. This good result is accompanied by v_1 time constant increase and, consequently, by incoming photons measuring rate range decrease. Active quenching and active reset are the procedures to overcome it.

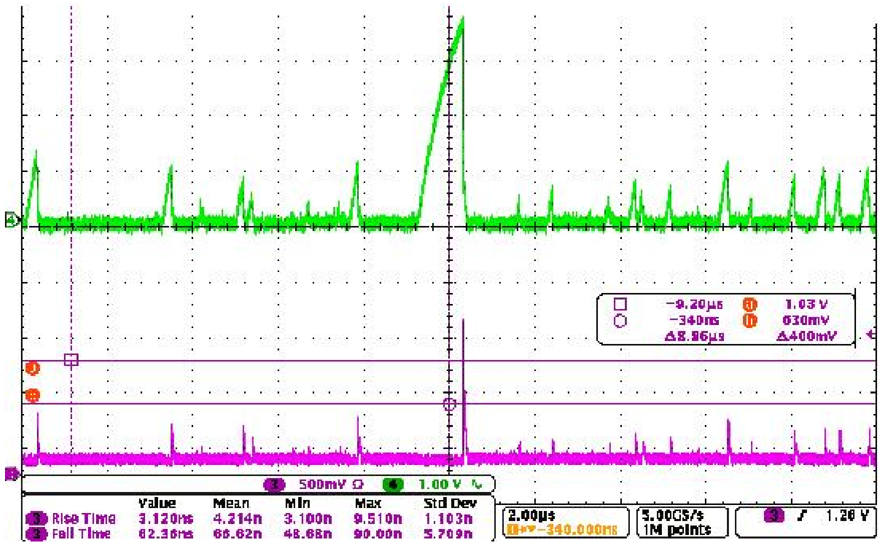


Fig. 6. The avalanche does not quenche for long time intervals when the ballast resistor is small enough: ch. 3 – input voltage v_i; ch. 4 – APD cathode voltage v_1.

4. ACTIVE QUENCHING

There are many techniques to apply active quenching; a comprehensive revue was written by Cova [2]. Below, we describe the working principle of the implemented method.

When an avalanche takes place, K1 (see Fig. 7) turns on, an input pulse, v_i, is detected, K2 turns on at an electronic command and the quenching voltage VQ is applied to the APD anode.

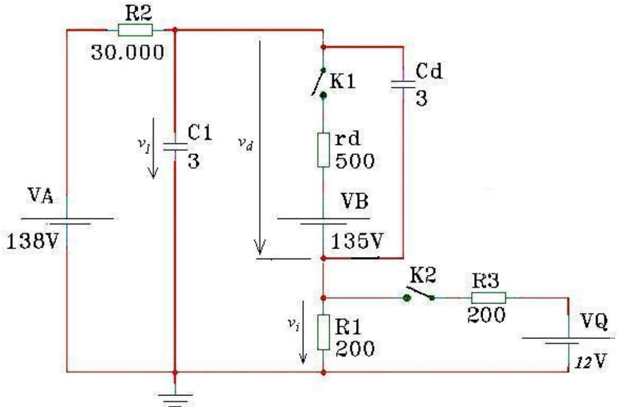


Fig. 7. An active quenching circuit – simplified scheme.

As a result, the voltage, v_d, across the diode decreases below the breakdown voltage and the avalanche ceases. This is why the ballast resistor, R2, can be drastically decreased. Nevertheless, we kept for it a significant value in order to limit, to a safe level, the dissipated power on the APD, just in case something goes wrong. The v_1 exponential increase starts when VQ is removed (see Fig. 8).

The time to reach the maximum excess voltage, VE, can be further reduced adding active reset [2]. The overall result can be seen in Fig.9: the minimum time between two successive pulses is about 0.2 µs; even smaller than 0.1 µs is already obtained.

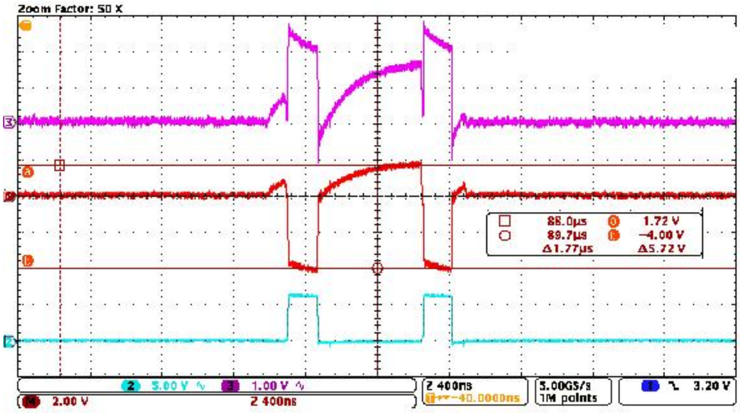


Fig. 8. Actual waveforms for an active quenching circuit: v_i = ch. 2; v_d = ch. M; v_1 =ch. 3.

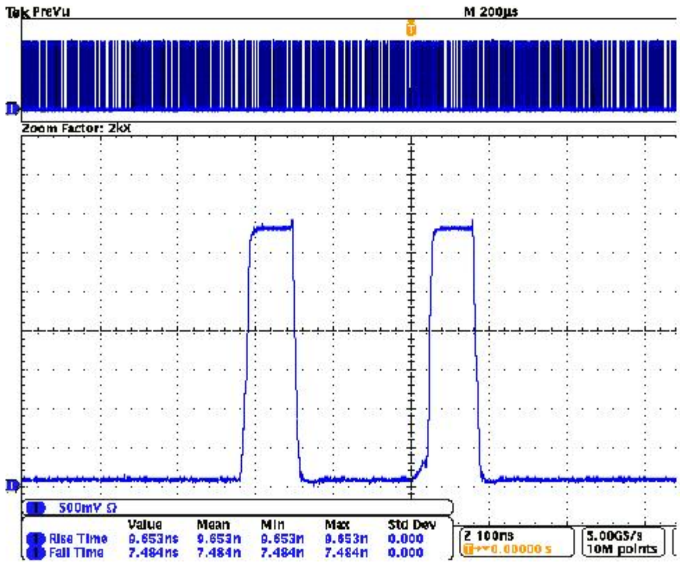


Fig. 9. v_i waveform of an active quenching and active reset circuit.

5. SINGLE PHOTON DETECTION MODULE: FUNCTIONAL SCHEME

Because of application specifics, two similar single photon detection channels are considered.

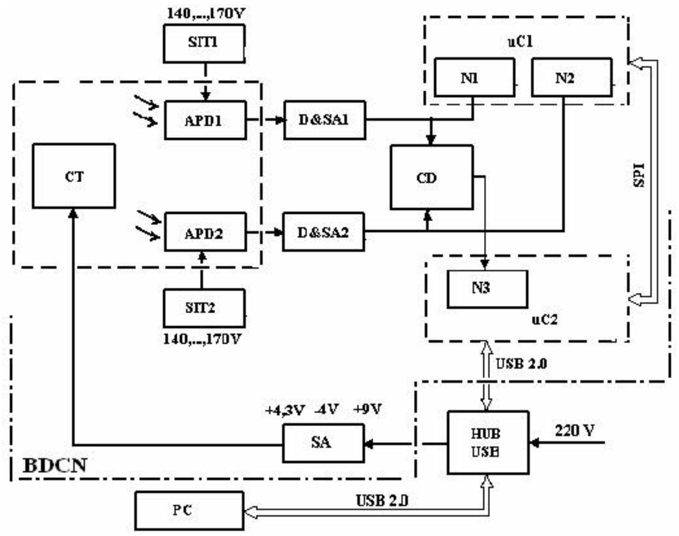


Fig. 10. The functional scheme of the detection module: CT – temperature controller; APD1, APD2 – avalanche photodiodes; D&SA1, D&SA2 – detection, active quenching and active reset circuits; N1, N2, N3 – counters; CD - direct coincidence circuit; SIT1, SIT2 – high voltage power supplies, SA – low voltage power supplies, PC – personal computer.

The two APDs and their associated detecting, active quenching and reset circuits, D&SA1, D&SA2, (see Fig. 10) supply standardized pulses both to N1, N2 counters and to the direct coincidence circuit, CD. The time-coincident pulses are counted by the N3 counter. The accumulated data are red by a personal computer, PC, through an USB 2.0 serial bus. To set and keep the working temperature of the APDs, a temperature controller, CT, is used. Adequate power supplies were provided.

6. THE FIRMWARE, DEVELOPING APPLICATIONS AND ACQUISITION SOFTWARE

The detection module, seen by a programmer, is made of two PIC18F4455 (Microchip) microcontrollers as represented in Fig. 11. Counter N3 is implemented on the master, while counters N1 and N2 lay on the slave. The two controllers communicate with each other through an SPI interface. The master communicates to the PC through an USB 2.0 interface. Both SPI and USB are controlled using built in modules of the PIC controllers.

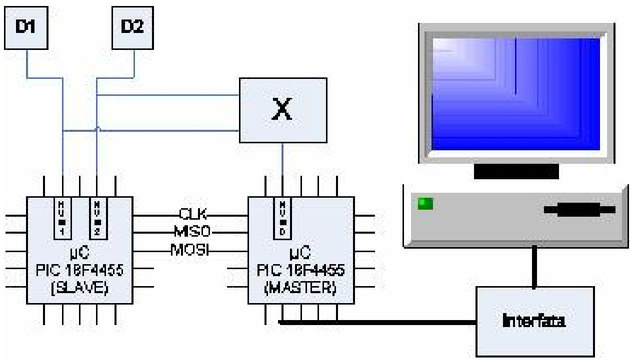


Fig. 11. The detection module seen by a programmer: D1, D2 – detection and quenching circuits; X – direct coincidence circuit; µC – microcontrollers. The microcontrollers communicate using an SPI interface. The whole module is connected to the PC through USB2.0 interface.

The adopted application software architecture (see Fig. 12) refers to both the firmware installed on microcontrollers and the software resident on the PC. The modular structure eases the processes of development and maintenance. The source code for the PC is written using Visual C++ . The firmware was written using PIC assembly language, translated to machine language by using the MPLAB application provided by Microchip.

The software application allows: acquisition time setting, counters' reading, data storing, graphical interface and friendly reports. The graphical user interface (see Fig 13) was designed to attach automatically a unique name - "Raport_masurare_data_ time"- to each measuring report, to reserve locations for the operator's notes, to set the measuring time, to display the acquisition results both as total rate (R.T), and net rates (R.N.). The standard deviations are also calculated.

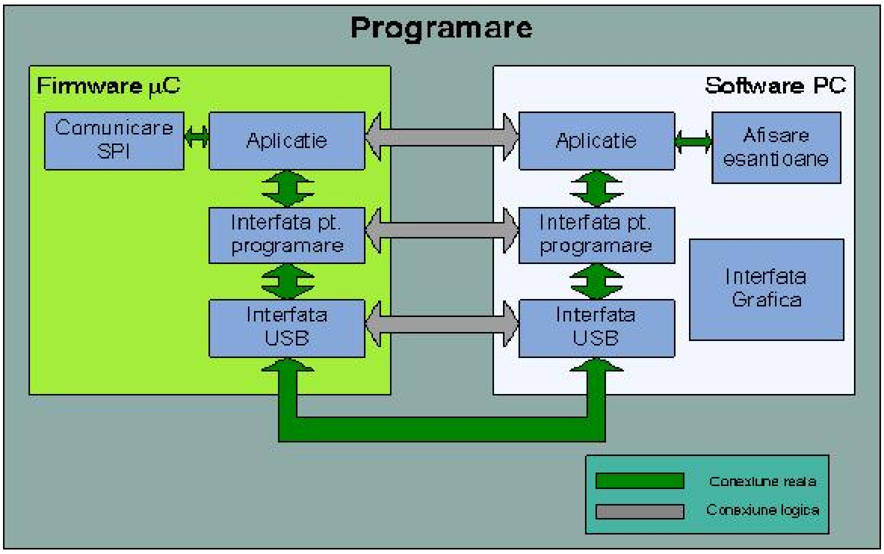


Fig. 12. Application software architecture

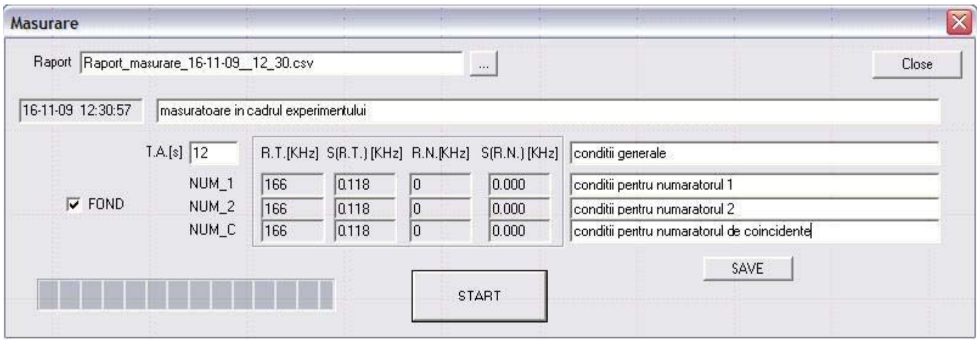


Fig. 13. The graphical user interface of the single photon detection module.

7. THE OPTICAL SYSTEM

The optical system assures both the optical coupling of the APD to the field to be measured and isolation against the ambient light.

The female FC connector (see Fig. 14) allows the coupling of an optical fiber. Lens L1 transforms the input divergent light beam into a parallel one, whereas L2 concentrates it on the active area of the APD. The tube T is necessary to thermally isolate the APD subassembly from the front panel.

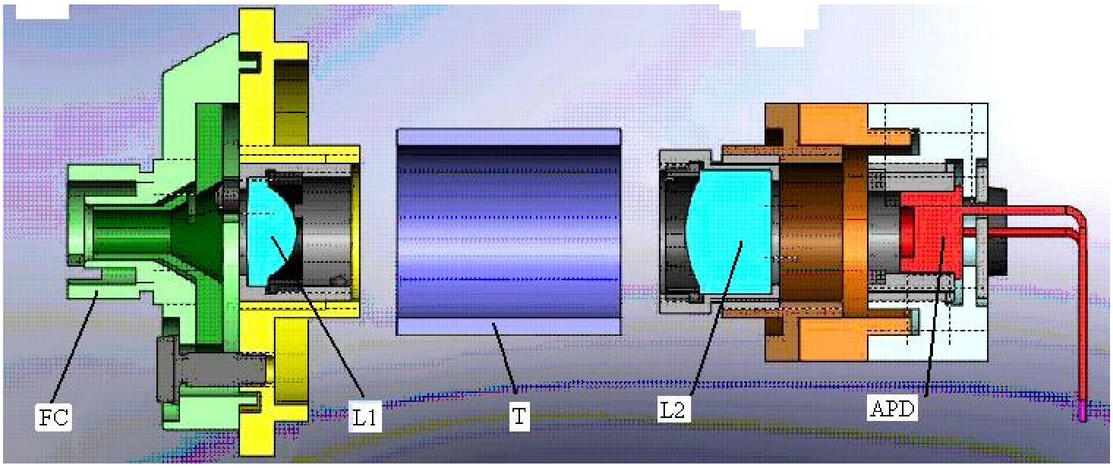


Fig. 14. The optical assembly of the single photon detecting module: FC – female FC connector, L1 and L2 – lenses, T – thermally isolating tube, APD – the transducer.

The most difficult problem is to shield the single photon detector against the ambient light: neither the labyrinth type mechanical coupling nor the isolation assured by the textolit tube are efficient. Even more: the electric isolating pearls, mounted on the APD pins, transmit light. The solution is to use an adequate paint when assembling.

8. REGULATED TEMPERATURE SYSTEM

At the first sight, this system can be considered as simple one. It is not! It involves both the electronic temperature controller and the rest of the module: all parts are thermally interconnected.

The power, P_d, dissipated by the APDs has to be taken out from the thermal isolated case by the thermoelectric cooler (TEC). To do that, the TEC is supplied with the electric power, P_E, (greater than P_d) witch is dissipated as heat and increases the temperature all around the thermal isolated case. The equivalent thermal resistance between the inside and the outside of the case is not infinitely large, so a coupled power, P_c, reaches the cold components and has to be removed. A higher electric power is supplied, an outside temperature increase follows, a higher coupled power reaches the cold components and so on. It is a positive feedback [4]! Fig. 15 illustrates it.

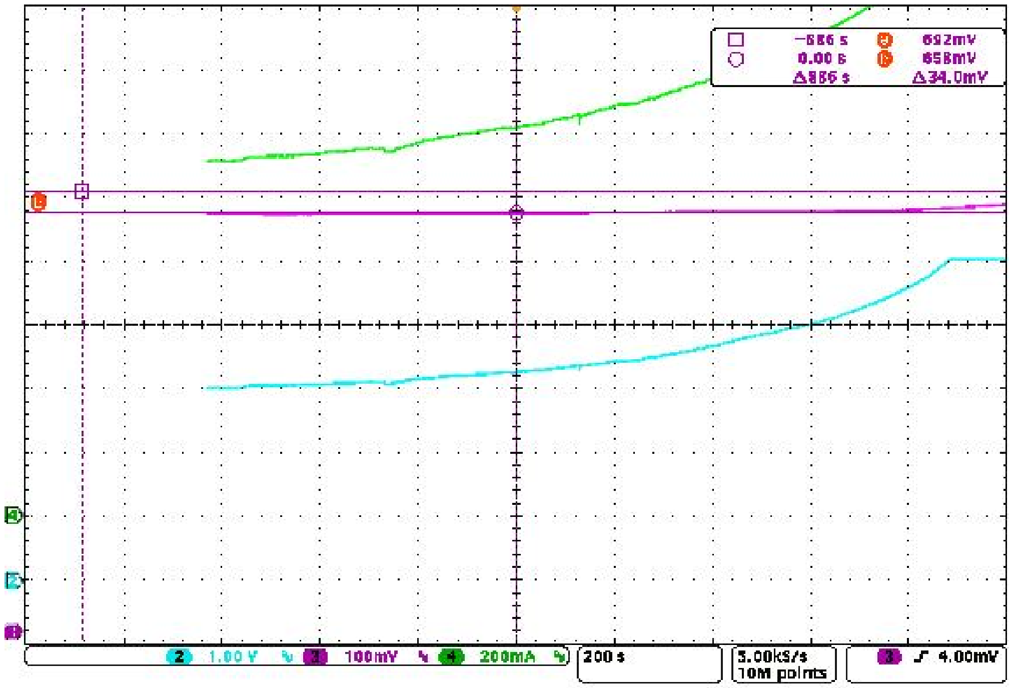


Fig. 15. The cold point temperature cannot be assured for long time because of the thermal positive feedback: Ch.1 - cold point temperature; Ch. 2 – voltage across the TEC; Ch. 4 – current intensity through the TEC.

A good design, from thermal point of view, is mandatory. We have adopted the one illustrated in Fig. 16. The external isolation is made from extruded polistyren. The rigid parts are made from textolit. Metal components were avoided as much as possible. The results can be seen in fig. 17.

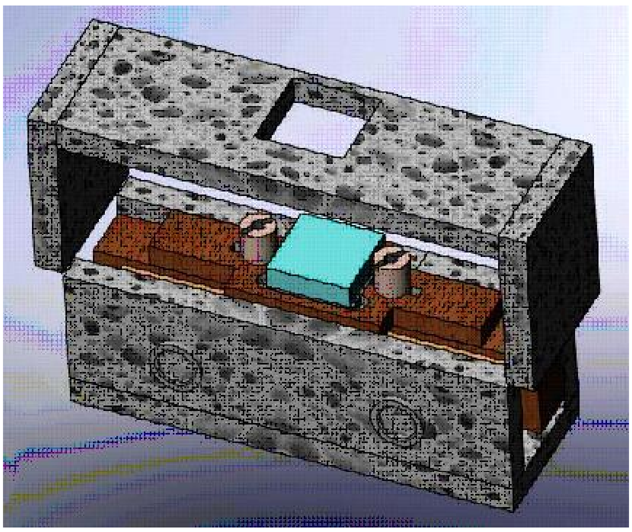


Fig. 16. The thermal isolated case. The external isolation is made from extruded polistyren. Inner parts are made from textolit. Metal was avoided as much as possible.

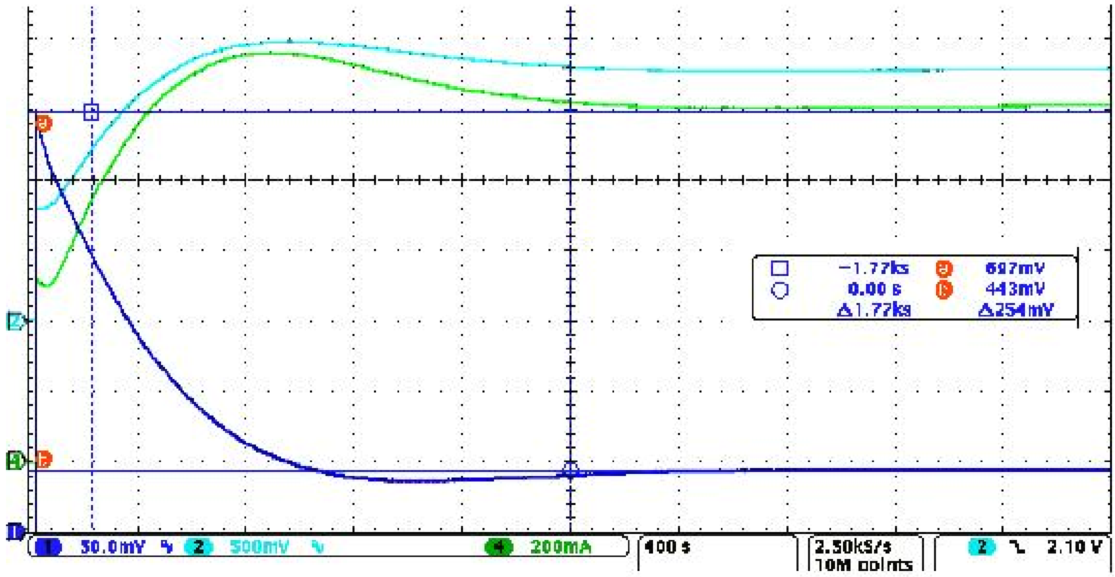


Fig. 17. The temperature controller response: Ch. 1– cold point temperature (initial temperature +19.7 °C, final temperature -5.7 °C); Ch.2 – voltage across the TEC; Ch. 4 – current intensity through the TEC.

9. CONCLUSIONS

To design the module, some parameters of the APD have been measured using the authors' methods.

The single photon detecting module's main characteristics are the following:

- the background rate – 5kPPS,
- measuring range – [1;1000] kPPS when acquisition time is 10 s,
- spectral range – (400; 900) nm,
- command and control through a PC,
- thermal stabilization of the APD at -5.4 °C,
- working temperature range [0; 25] °C.

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