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Large area silicon photomultipliers allow extreme depth penetration in time-domain diffuse optics

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***Abstract*—We present the design of a novel single-photon timing module, based on a Silicon Photomultiplier (SiPM) featuring a collection area of 9 mm^2. It reaches a Single-Photon Timing Resolution of about 140 ps, thus being suitable for diffuse optics application. The small size of the instrument (5 cm x 4 cm x 10 cm) allows placing it directly in contact with the sample under investigation, maximizing that way the signal harvesting. Thanks to that, it is possible to increase the source detector distance up to 6 cm or more, therefore enhancing the penetration depth up to an impressive value of 4 cm and paving the way to the exploration of the deepest human body structures in a completely non-invasive approach.**

Keywords—Silicon Photomultipliers; Time Domain Diffuse Optics; Time-Correlated Single-Photon Counting;

I. INTRODUCTION

A growing interest for clinical diagnostic imaging is spreading in the last decades; among all the imaging techniques, only few of them are completely non-invasive. This is the case of Diffuse Optics (DO) [1] since by injecting light within the 600-1000 nm range and collecting photons re-emitted from the diffusive medium at a certain distance ρ, it is possible to characterize the sample optical properties, which are strictly related to the tissue composition. By the means of this technique it is possible to study a wide number of biological tissue such as the brain [2] or the breast [3], or assess the quality of food [4] and many others. The traditional DO approach makes use of a continuous wave (CW) laser source. In this case, upon increasing ρ, deeper layers inside the sample are probed. Alternatively, it is possible to use a Time Domain (TD) technique. In TD-DO a pulsed laser is injected into the sample: in this way photons that have investigated deeper layers are the ones that are re-emitted at later times t [5]. The penetration depth in TD-DO is independent of the source-detector distance, but the use of large distances can reduce the amount of early photons with respect to the useful late ones. While travelling into a scattering medium, light is strongly attenuated, thus resulting into a very faint re-emitted signal; hence, by increasing the ρ, the collected light intensity is reduced. For this reason it is mandatory to employ large-area photodetectors in order to maximize the light harvesting.

Photocathode-based detectors such as PhotoMultiplier Tubes (PMTs) have been widely used in TD-DO [6] thanks to their large active areas, but they are bulky, expensive and fragile. Additionally, they are sensitive to high light exposure. Only recently Silicon Photomultiplier (SiPMs) have been proposed as a possible revolutionary alternative to PMTs [7], [8] thus resulting in an impressive reduction in the whole system complexity and cost and paving the way to the design of novel TD-DO systems, where hundreds of channels can be easily parallelized.

A SiPM is made by an array of thousands microcells, each one including a single-photon avalanche diode (SPAD) and a passive quenching resistor; all the cells are connected together to create a single global anode and a single global cathode [9].

Replacing traditional PMT with SiPMs can bring a number of advantages such as: (i) wide active area (up to few mm^2) and numerical aperture, thus giving an extreme photon harvesting capability, (ii) broad spectral usage range (400-1100 nm), (iii) good temporal resolution (less than 100 ps) [10], (iv) extreme compactness, (v) insensitivity both to magnetic field and high light exposure, (vi) CMOS process compatibility that can allow the integration of the detector with all the ancillary electronics on the same chip [11].

In this paper we present the design of a completely stand-alone SiPM-based single-photon timing module, employing a commercial 9 mm^2 active area device (S13362-3050DG, Hamamatsu Photonics, Japan). We firstly describe the module structure and electronics, then we characterize the Single-Photon Time Resolution (SPTR) to validate the feasibility of the system for TD-DO applications. We measure the light harvesting efficiency and, in the end, we explored the capability of the instrument to detect the contrast produce by a fully absorbing inclusion into an homogeneous liquid phantom by comparing both a 9 mm^2 SiPM and a 1 mm^2 one, therefore proving that the higher collection area allows to increase the source-detector separation and reach deeper regions into the sample.

II. INSTRUMENT DESCRIPTION

Figure 1 shows the block diagram of the module: the “front-end” board is designed to extract the single photon signal from the 9 mm^2 SiPM. When a photon reaches the detector’s active area and triggers the avalanche pulse, a RC network couples the signal to the RF amplifier that generates

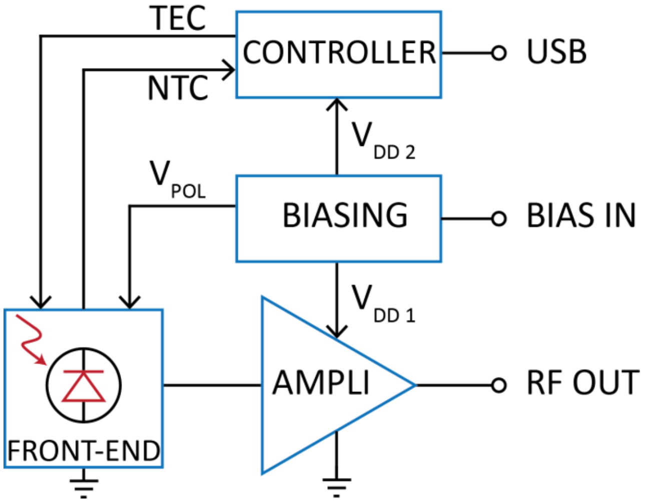

Figure 1. Block scheme of the module: the CONTROLLER board sets the device temperature thanks to a Peltier element, being also able to monitor it by the means of a negative temperature coefficient (NTC) resistor. The BIASING board provides all the supply voltages of the module from a global bias input. The RF amplifier (AMPLI) extracts the analog output of the SIPM from the FRONT END that embeds the detector together with the passive readout network.

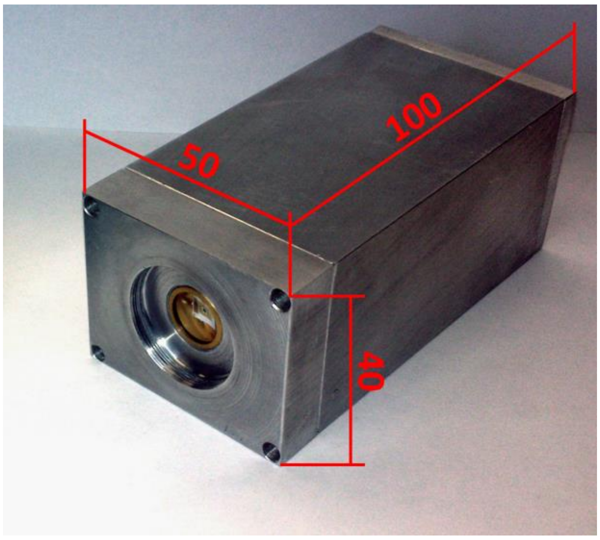

Figure 2. Picture of the module highlighting the compact dimensions (expressed in millimeters).

the output of the module. The design of the RF layout is fundamental to preserve the detector intrinsic temporal resolution by avoiding the degradation of the fast (~1 ns) and faint (~1 mV) avalanche pulse. The SiPM is packaged with a Thermo-Electric Cooling (TEC) Peltier element. A “TEC Controller” board is able to precisely set (with 0.001°C resolution) the device operative temperature. A Negative Temperature Coefficient (NTC) resistor is used to monitor it. The temperature can be chosen in the range between -10°C and 50°C by programming the controller thanks to an USB connection. Finally the “biasing” board provides all the necessary supply voltages starting from a common plug in AC power adapter. The global power consumption of the module mainly depends on the TEC controller output current, reaching a maximum value of 6 W when the device temperature is set at -10°C.

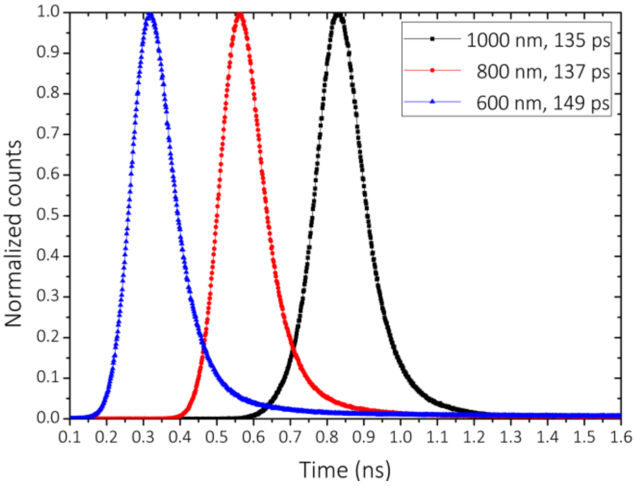

Figure 3. Single photon IRF of the system highlighting the single-photon timing resolution with the FWHM of the curve. Three wavelength are shown that cover the DO spectrum of interest.

Figure 2 reports a picture of the module: the SiPM is biased at an excess bias value $V_{EX} = 6$ V, where V_{EX} is defined as the difference between the biasing voltage V_{POL} and the detector breakdown voltage V_{BV}. Having such a V_{EX} and cooling the detector at 0°C brought to a total Dark Count Rate (DCR) of about 150k counts per second (cps).

III. MODULE CHARACTERIZATION

A. *Single photon timing resolution*

To evaluate the module Single-Photon Timing Resolution (SPTR) we acquired the Instrument Response Function (IRF) using a sharp (~10 ps) laser pulse by the means of the Time-Correlated Single-Photon Counting (TCSPC) technique [12]. We employed the same set-up described in [10]. The histogram of the arrival times of detected photons is reconstructed thanks to a TCSPC board (SPC130, Becker & Hickl GmbH, Germany). The module output provides the “stop” signal to the timing board, while the “start” one is given by the laser synchronism at a repetition rate of 40 MHz. The total photon detection rate was always kept below the few percent of the laser repetition rate, therefore having a negligible pile-up distortion [12]. The SPTR is calculated as the Full-Width at Half Maximum (FWHM) of the IRF curve.

Figure 3 displays the IRFs acquired at three wavelengths (i.e. 600 nm, 800 nm, 1000 nm), the curves show a constant shape over the wavelength spectrum and point out a SPTR

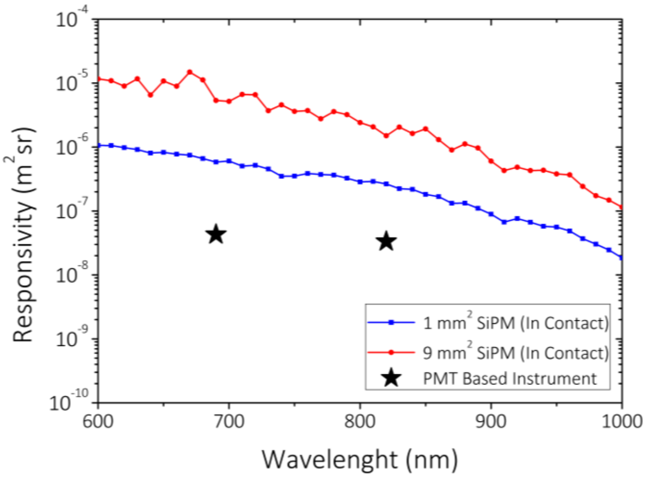

Figure 4. Optical responsivity of the 9 mm^2 SiPM module in contact with the sample compared with the 1 mm^2 one and with a PMT-based instrument employing 3 mm core optical fibers bundle.

of the detector around 140 ps, thus proving the suitability of the SiPM for the TD-DO applications.

B. *Spectral Optical Responsivity*

In order to evaluate the light harvesting efficiency of the module, we measured the responsivity parameter as described in the Basic Instrument Performance (BIP) protocol [13]. Compared to the single-photon detection efficiency (PDE), the responsivity parameter takes also in consideration the detector numerical aperture and active area fill factor. To measure it, we placed the module directly in contact with the reference calibrated phantom, therefore exploiting the whole numerical aperture of the detector and avoiding any signal losses due to fiber coupling, thus achieving the maximum light collection. In Figure 4 are reported the obtained results. The module embedding the 9 mm^2 detector shows an impressive increase of the responsivity value of two orders of magnitude with respect to a PMT-based state of the art instrument [6]. The figure also compares the responsivity of an identical module embedding instead a 1 mm^2 SiPM; in this case the value is one order of magnitude higher since the responsivity linearly depends on the total active area.

C. *Contrast measurements*

According to the nEUROPt protocol [14], we characterized the system capability of detecting the contrast produced by a totally absorbing inclusion made by a black cylinder with 100 mm^3 volume, corresponding to a $\Delta\mu = 0.15$ cm^{-1} over a volume of 1 cm^3 [15] . The cylinder is aligned to the middle point of ρ and it is moved along an increasing depth z (ranging from 2.5 mm up to 50 mm) inside an homogeneus liquid phantom, which optical properties were: (i) absorption coefficient $\mu_a = 0.1$ cm^{-1}, (ii) reduced scattering coefficient $\mu_s' = 10$ cm^{-1}. The optical properties are obtained by mixing a precise quantity of both Intralipid-20%, India ink and water, whose optical properties are well characterized [16].

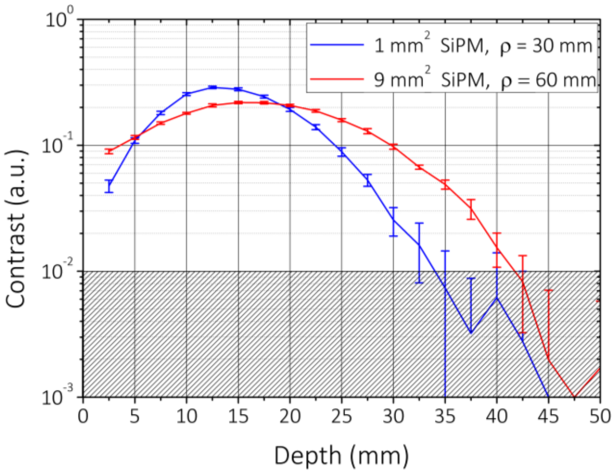

Figure 5. Contrast (C) produced by the totally absorbing inclusion as a function of the depth. A C = 1% is identified as the minimum detectable threshold. The 9 mm^2 SiPM is able to detect C = 1% at the depth of around 4 cm when the distance ρ is fixed at 6 cm. Instead the 1 mm^2 detector can reach a maximum depth of around 3cm, employing a ρ = 3 cm.

As a laser source, we used a commercially available pulsed laser diode (PDL, Picoquant, Germany) at the wavelength $\lambda = 690$ nm and 40 MHz repetition rate. The laser was able to deliver a maximum average power of about 1 mW, keeping the FWHM of the laser pulse under 100 ps.

Thanks to the high signal harvesting, we were able to use a $\rho = 60$ mm for the 9 mm^2 detector, while for the 1 mm^2 we used $\rho = 30$ mm. Figure 5 reports the contrast as a function of the inclusion depth, calculated as $C = (N_0\text{-}N)/N_0$, where N_0 is the total number of photon counts for the unperturbated case (i.e. inclusion removed from the phantom), while N is the same entity for the perturbated case. The 1 mm^2 SiPM module can detect the inclusion, with a contrast C = 1% (which is usually consider as the smallest contrast detectable) down to a depth of about 3 cm (close to the state of the art system for TD-DO [6]). Instead, keeping the same threshold of C =1% , the 9 mm^2 is instead able to reach the impressive depth of 4 cm.

IV. CONCLUSION

We presented the design of a novel single-photon timing module based on a SiPM with a photosensitive area of 9 mm^2. The module features a SPTR of about 140 ps within the 600-1000 nm wavelength range. This temporal resolution is suitable for time-domain diffuse optics application.

Thanks to its compact dimensions (5 cm x 4 cm x 10 cm) the module can be placed in direct contact with the sample, thus maximizing the signal harvesting and allowing to increase the source detector separation in TD-DO applications up to 6 cm or more. We obtained the impressive capability of the system to detect the contrast produced by an absorbing inclusion inside a homogeneous phantom down to a 4 cm depth when using a 1mW average power laser. This (together with an increased laser power) can pave the way to the use of SiPMs for the study of the deepest organs inside the human body (i.e. liver, heart, lungs, etc.) in a completely non-invasive way.

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