Pushing Time-Domain Diffuse Optics to Its Ultimate Limits: New Large-Area Detector and Operation Modality

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Abstract: Large area single-photon detectors enhance light harvesting capability beyond state-of-the-art provided that pile-up distortion is corrected. We test a 10 x 10 mm^2 SiPM-based detector and study the possibility to work beyond singe-photon statistics. © 2022 The Author(s)

1. Introduction

Time Domain Diffuse Optics (TD-DO) allows to non-invasively investigate highly scattering medium (e.g., biological tissues, wood, and fruit) gathering information about its composition and microstructure [1]. This technique bases on the injection of picosecond laser pulses (~100 ps) in the medium and on the time-resolved detection of re-emitted photons at a distance ρ from the injection point, which are then classified using the Time-Correlated Single Photon Counting (TCSPC) technique. The TD approach has some important features, such as the capability to retrieve independently absorption and scattering information and, in reflectance geometry, the capability to encode depth information in photon arrival time. Because of the high information content, significant efforts have been made in the last decade to accelerate technological advancements for pulsed laser sources, single-photon detectors, and timing electronics, enabling the transition from bulky and expensive systems to compact, low-cost, and even wearable cutting-edge devices.

To push TD-DO to its limits (studying even structures at depths greater than 5 cm), single-photon sensitive detectors with extremely large collection areas have been developed within ATTRACT project SP-LADOS. In particular, a 10 x 10 mm^2 SiPM-based detection module has been realized, boosting the light harvesting capability by almost one order of magnitude above standard detectors. To use its whole collecting capability and avoid signal attenuation (necessary to remain into single-photon statistics), the operating condition of extremely high count rates (CRs) needs to be investigated. Hence, is such condition, strong pile-up distortion affects the signal and suitable correction strategies must be implemented [2]. This regime has never been systematically studied for TD-DO and could be a promising working modality for new TD-DO instruments and their broad use in everyday life.

In this study, we present the new large-area detector as well as preliminary simulation results mimicking the extremely high count rate operation. We adopt the methodology and the figure of merits (FoMs) of MEDPHOT and nEUROPt protocols (well-accepted procedures for evaluating DO instrument performances) [3] to objectively assess the performances obtained in this new working regime.

2. Results

The 10 x 10 mm^2 SiPM-based detection module has been developed by FBK (Trento, Italy) [4]. In this study, we evaluate the in-statistics performances of this large-area detector.

The MEDPHOT experiments have been conducted with the MEDPHOT phantom kit, consisting of 32 homogeneous solid phantoms with 4 reduced scattering coefficients (conventionally true $\mu_s' = 7, 11, 16, 20$ cm^{-1} at 690 nm) and 8 absorption coefficients (conventionally true $\mu_a = 0.01, 0.07, 0.14, 0.20, 0.27, 0.33, 0.38, 0.46$ at 690 nm). The absorption linearity (FOM showing the dependence of the measured μ_a against its nominal value) for the different scattering series is shown in Fig. 1 (left). It is possible to see a good linearity in all the cases (slopes close to 1, see dashed line in Fig. 1). Even μ_s' shows good linearity (data not shown). Thus, the new large-area detector can successfully retrieve homogenous phantom optical properties. The nEUROPt measurements have been performed with a liquid phantom ($\mu_a = 0.1$ cm^{-1} and $\mu_s' = 10$ cm^{-1}) where a totally absorption inclusion (equivalent $\Delta\mu_a = 0.17$ cm^{-1} over 1 cm^3, at 670 nm) was moved in depth [5]. The computed contrast-to-noise ratio -CNR- (i.e., the ratio between the absolute changes in the number of counts produced by the perturbation and the fluctuations in the number of counts of the homogenous state, within gates of 1 ns width) as a function of the perturbation depth for different gates is reported in Fig. 1 (right). It improves with the gate delays and, for the late gates (4-5 ns and 5-6 ns), is bigger than 1 (the theoretical limit for visibility, grey region) up to 40 mm. Even the contrast -C- (i.e., the relative change in the number of counts produced by the perturbation in the same gate windows as before) is bigger than 1% up to 40 mm (data not shown).

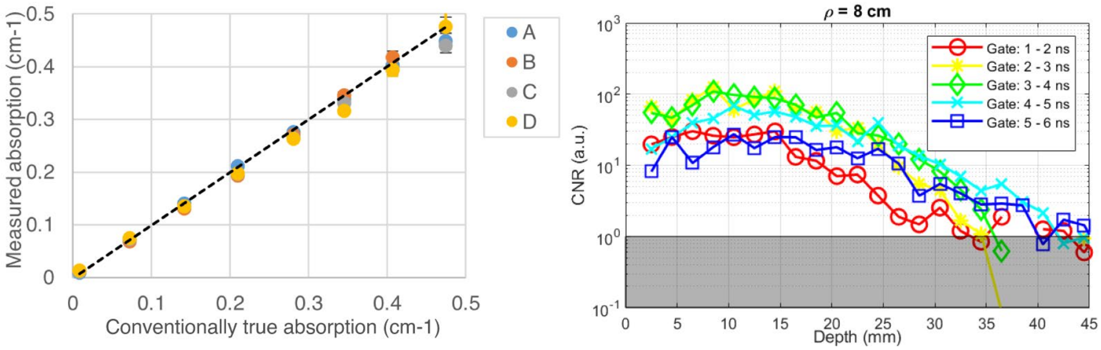

Fig. 1. Linearity (left) and contrast to noise ratio (right) of the 10 x 10 mm^2 SiPM- module.

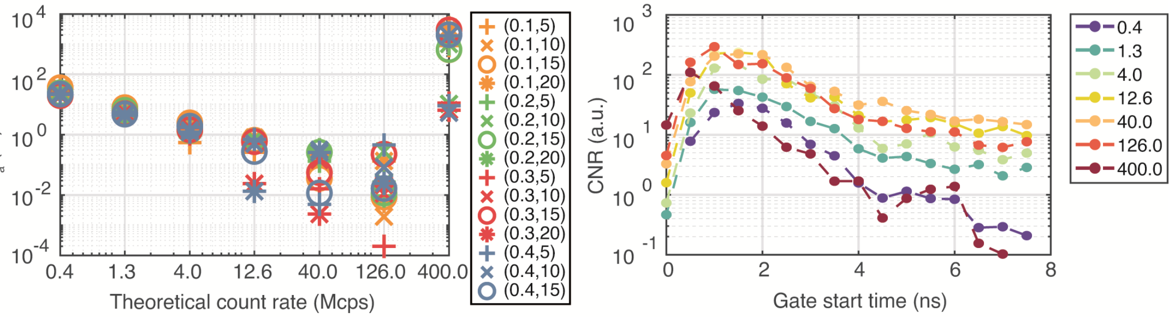

Fig. 2. Simulated accuracy for different μ_a and μ_s' (left) and contrast to noise ratio (right) at different count rates.

These two conditions together grant the detectability of localized perturbation up to 40 mm from the surface, opening the way to use the 10x10 mm^2 SiPM module for in-depth probing.

Simulations of distribution of times of flight (DTOF) of backscattered photons have been carried out using radiative transfer equation under diffusion approximation for semi-infinite medium. Particularly, we consider both homogenous and embedded localized absorbing perturbation cases. To simulate performances achievable with pure in-silico TD-DO system, we convolved the theoretical DTOF with the Instrument Response Function (IRF) of a typical SiPM detector. Further, we consider: a laser rate of 40 MHz, a TCSPC channel width of 5 ps, and a ρ of 3 cm. For the nEUROPt analysis we use a medium with $\mu_a = 0.1$ cm^{-1} and $\mu_s' = 10$ cm^{-1} embedding a perturbation with $\Delta\mu_a = 0.17$ cm^{-1} in 1 cm^3 volume, placed at half of the ρ and at a depth of 1.5 cm. The effect of the pile-up has been simulated distorting the DTOF using a MATLAB code based on random Poisson launches and then it has been corrected as detailed in Ref. [2]. We simulate 7 different theoretical CRs (considered after pile-up correction) spanning a range well-within and far-beyond single photon statistics (where the CR is limited to 1-5% of the laser rate): 0.4, 1.3, 4.0, 12.6, 40.0, 126.0 and 400.0 Mcps. For MEDPHOT protocol we consider 16 homogenous phantoms (4 $\mu_s' = 5, 10, 15, 20$ cm^{-1} combined with 4 $\mu_a = 0.1, 0.2, 0.3, 0.4$ cm^{-1}). For all of the simulated MEDPHOT phantoms, the after-correction absorption accuracy (i.e., percentage difference between the retrieved μ_a and the true one) is represented in Fig. 2 (left). Thanks to the correction, at 126 Mcps an average error smaller than 1% can be obtained. However, it appears that the correcting procedure is insufficient to retrieve the optical property at the extreme CR (400 Mcps). Fig. 2 (right) shows the CNR vs gate starting time, for all the CRs. As expected, CNR improves in high-throughput cases thanks to the increased number of detected photons, but for last two CRs, it starts decreasing because of the noise amplification introduced by the pile-up correction. Hence, simulations show that TD-DO in high CR regime is feasible, when correction strategies are employed.

3. Acknowledgements

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4. References

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