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Preliminary Design of the Hybrid Digital Optical Module for TRIDENT

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Hybrid Digital Optical Module (hDOM) is a newly designed detection unit for the proposed deep-sea neutrino telescope in South China Sea, TRopIcal DEep-sea Neutrino Telescope (TRIDENT). Each hDOM is equipped with multiple PMTs for uniform angular acceptance and additional silicon photomultipliers (SiPMs) with O(100) ps timing response. The combination of these two kinds of optical sensors can significantly improve the detector's angular resolution, boosting the detector's capacity searching for neutrino sources. Many challenges also arise due to the limited space in the glass vessel, power consumption and data transmission bandwidth. This contribution will present the current progress of the preliminary design of hDOM, including its mechanical structure and electronics.

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1. Introduction

TRopIcal DEep-sea Neutrino Telescope, TRIDENT, is a next-generation deep-sea neutrino telescope proposed to be deployed in South China Sea [1]. TRIDENT aims to discover multiple high-energy astrophysical neutrino sources and provide a significant boost to the measurement of cosmic neutrino events of all flavors.

In September 2021, TRIDENT successfully conducted its pathfinder experiment, which involved measuring the optical properties of seawater and determining a scattering length of approximately 63 m for Cherenkov light [1]. In comparison to ice, water exerts a weaker effect on photon scattering, leading to superior time resolution. For example, the geometric scattering length of the ice layer between 1450 m and 2450 m in IceCube in Antarctica ranges from 0.3 m to 5.4 m [2]. Furthermore, silicon photomultipliers (SiPMs) demonstrate faster time response and higher precision in time resolution compared to traditional photomultiplier tubes (PMTs) and can achieve a single photon time resolution (SPTR) on the order of 100 picoseconds [3].

TRIDENT will utilize a hybrid Digital Optical Module, named hDOM, which combines large-area PMTs and fast-response SiPMs, aiming to maximize the angular resolution of water-based neutrino telescopes. To meet the granularity requirements and account for mechanical constraints, hDOM will arrange 31 PMTs on the glass sphere to capture photons in all directions. Additionally, hDOM will incorporate 24 SiPM arrays arranged between the PMTs, each with a sensitive area of 7.3 cm^2. Based on our previous simulation, assuming the PMTs' transit time spread (TTS) of 5 ns and the SiPM arrays' SPTR of 0.1 ns, the angular resolution of a neutrino teleacope that has 5000 hDOMs forming a grid array in 1 km^3 for muon at 1 TeV is expected to improve by approximately 40 % compared to the configuration without SiPM arrays [4].

The hardware implementation of this design presents several challenges. Firstly, due to limited space, the mechanical structure needs to be tightly packed, and the electronics system requires highly integrated multi-channel readout capabilities. Secondly, the large number of PMTs and SiPMs results in significant power consumption and data transmission bandwidth requirements. Moreover, the increase in SiPM area leads to increased capacitance, which can significantly impact its time response performance [5].

In these proceedings, we will present our progress in the mechanical design of hDOM, which primarily includes the layout design of PMTs and SiPM arrays on the surface of the hDOM, as well as the design of the 3D-printed bracket. Furthermore, we will discuss our current progress in the performance of the SiPM front-end readout.

2. Preliminary Mechanical Design

2.1 hDOM Layout

The framework design of TRIDENT's hDOM is inspired by the multi-PMT optical module design of KM3NeT [6], another water-based neutrino telescope. However, hDOM will be pioneering in its use of SiPMs in a neutrino telescope, as it will incorporate an additional 24 SiPM arrays based on the 31 PMTs. SiPM is a significant highlight of the hDOM design, but it also introduces substantial challenges, such as the delicate balancing of the positioning and mounting of both PMTs and SiPM arrays.

As illustrated in Fig. 1, the four main mechanical components, from the outside inward, are the spherical glass shell, aluminum alloy cover, supporting bracket, and internal electronics assembly. The shell, manufactured from high-pressure glass by the Nautilus company, has an outer diameter of 17 inches and a thickness of 14mm and is also equipped with a vacuum nozzle and a penetration hole. The aluminum alloy cover, shaped like an umbrella, is closely fitted to the top of the glass shell and functions as the primary component for heat dissipation. The supporting bracket is a spherical shell used to firmly hold 31 PMTs and 24 SiPM arrays. The innermost assembly houses various electronic components and includes an auxiliary heat dissipation mechanism, which assists in maintaining a safe operating temperature. Finally, the optical glue will be used to fill between the photodetector surface and the glass shell to reduce the interface loss.

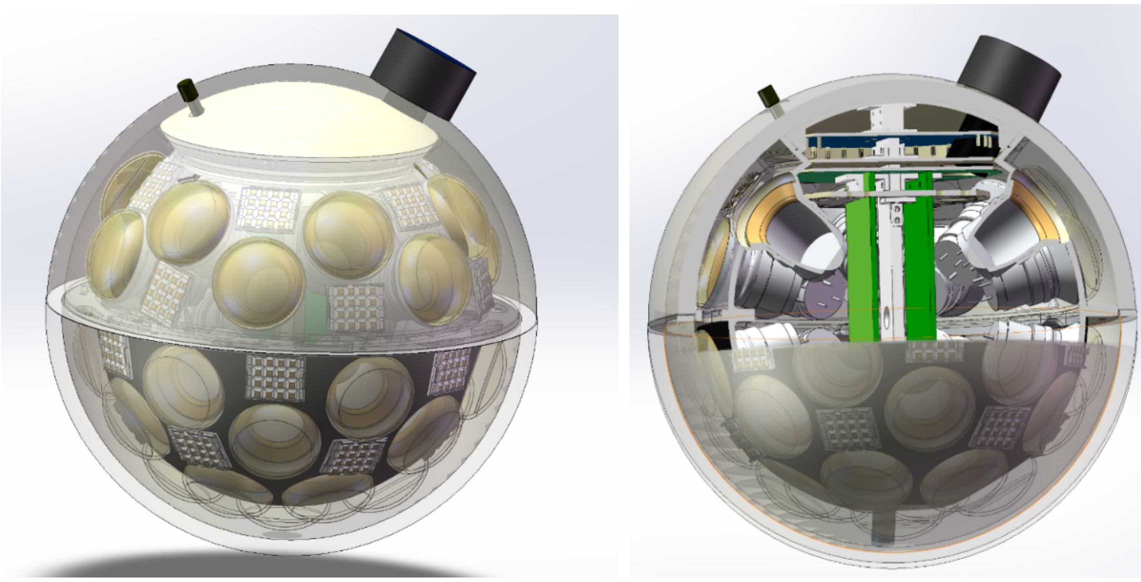

Figure 1: The 3D rendering of hDOM CAD model. Left: The overall view of hDOM from the outside. Right: The cross-sectional view of hDOM which reveals the internal structure.

2.2 The Supporting Bracket

A three-dimensional model of the hDOM was created using CAD software, with the primary technical challenges lying in the mounting techniques for the PMTs and SiPM arrays. Aside from a stable mounting scheme, an effective sealing strategy is essential to prevent optical glue leakage during the filling process. As illustrated in Fig. 2, the PMT is mounted using a custom-shaped support, featuring two internal grooves designed to accommodate a silicone sealing ring. Similarly, a rectangular bracket is designed to mount the SiPM array, with a silicon sealing ring used for sealing. Experimental validation has demonstrated that this sealing structure ensures no leakage of optical glue over 24 hours.

With photo sensors securely mounted on the brackets, we have created a 3D-printed spherical shell to house the brackets, as shown in Fig. 3. The PMTs and SiPM arrays are organized into rings of six, each orientated at distinct angles—49.7, 57, 72.3, 79, 100, 106.5, 122, 127.75, 149, and 180 degrees—from the zenith of the optical module. Within each ring, the PMTs are spaced at

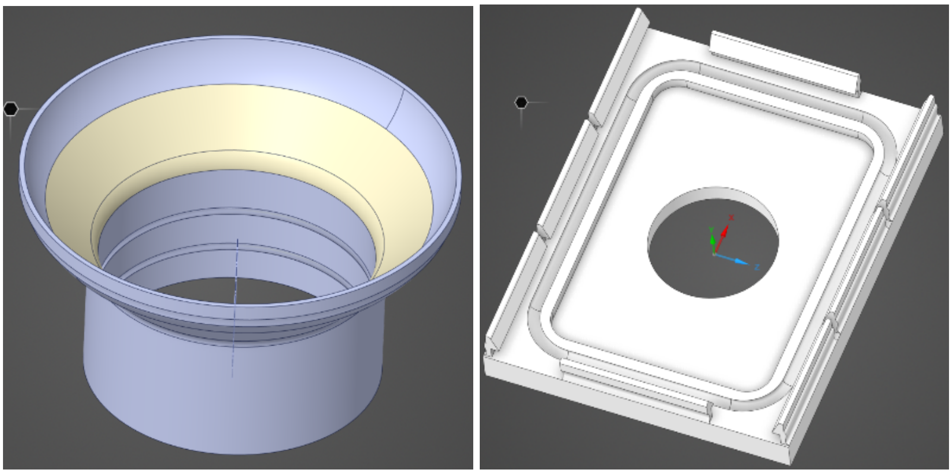

Figure 2: The CAD mounting model for PMT (left) and SiPM array (right).

60-degree intervals in azimuth, with neighboring PMT/SiPM rings offset by 30 degrees in azimuth. The configuration will place 12 PMTs and 12 SiPM arrays in the upper hemisphere, and 19 PMTs and 12 SiPM arrays in the lower hemisphere, respectively.

Figure 3: The 3D-printed shell to house the photo-sensor brackets. The left and right images show the upper and lower hemispheres, respectively.

2.3 Discussions

The structural integrity of our 3D-printed model confirmed through an optical gel injection test attests to the feasibility of our hDOM design. However, given our high standard for sustained optical transparency, we recognize potential challenges: the 3D-printing material can generate volatile organic molecules that might compromise the transparency of the optical gel over time, and the material itself is subject to aging over 10-20 years. These potential issues compel us to consider using a metal support structure similar to that of IceCube. Also, the introduction of the SiPM arrays necessitates an enhancement in our mechanical heat dissipation design, especially in comparison to the approach used by KM3NeT.

3. SiPM Front-end Readout Electronics

SiPM are composed of multiple pixels, each consisting of an avalanche diode operating in Geiger mode and a quenching resistance [3]. The specific SiPM model we have currently chosen is Hamamatsu S13360-3050. Each SiPM has a sensitive size of 3×3 mm^2 and contains 3600 pixels, with each pixel covering 50×50 μm^2 area.

For the readout of the SiPM signal, we have designed a non-inverting amplifier circuit and utilized the TEXAS OPA855 operational amplifier with a gain bandwidth product (GBP) of 8GHz [7]. Fig. 4-left presents the physical photograph of the circuit and the waveform of the single photon signal. With a voltage amplification of several tens, the bandwidth of the amplification circuit is on the order of 100 MHz. Fig. 4-right shows the waveform of the amplified signal, and demonstrates a fast-rising edge but a slower falling edge. SiPM has a high dark count rate (DCR) of about 50 kcps (kilo counts per second) per mm^2 at room temperature, which decreases by approximately one order of magnitude when the temperature is lowered to 2 °C. Due to the long duration of the falling edge, lasting approximately 100 ns, the high DCR can easily cause signal accumulation and drifted baseline. Therefore, filtering is necessary to mitigate these effects. We have designed a pole-zero cancellation circuit that introduces a new pole and zero to filter out most of the low-frequency signals, the significant reduction in waveform width after filtering is shown in Fig. 4.

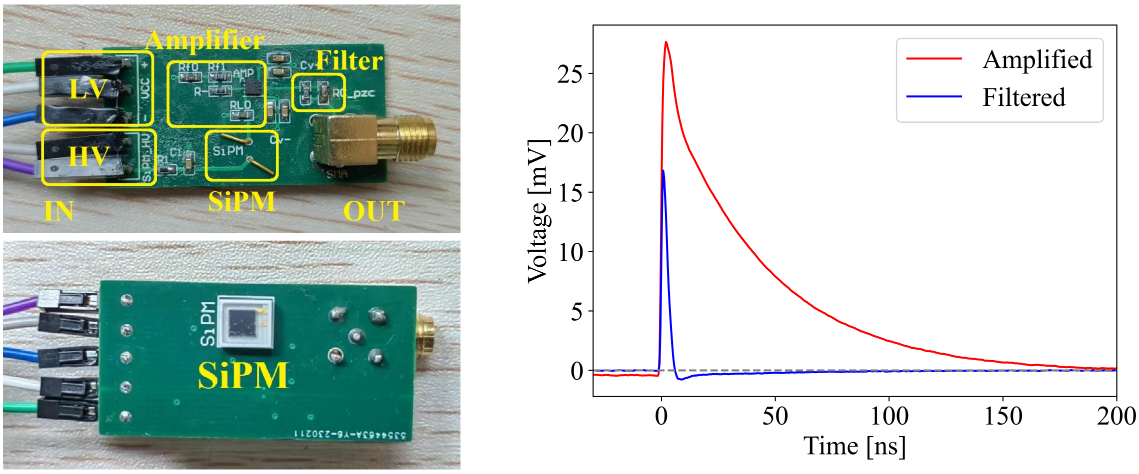

Figure 4: Left: the physical photograph of the SiPM front-end readout circuit, including amplification and filtering. Right: the average measured single-photon waveform, magnified by a factor of 41. The red and blue lines represent the waveforms before and after filtering, respectively. The rise time and fall time of the waveform are measured to be 1.64 ns and 90.5 ns respectively before filtering, and 1.12 ns and 3.45 ns respectively after filtering.

Based on the design requirements specified in [4], each SiPM array has a detecting area of 7.3 cm^2, equivalent to dimensions of 2.7×2.7 cm^2. Therefore, the number of SiPMs required for each array is 9×9. Integrating multiple SiPMs into a single readout channel presents several challenges due to the enlarged surface area. First, adding amplifiers to each of these SiPMs would result in high power consumption and inadequate space. For example, if the current amplification circuit consumes about 100 mW per channel, then the power consumption of each SiPM array will reach 8W. Second, if multiple SiPMs are read out in parallel, the increased area would lead to increased capacitance, thereby affecting the time performance. On the other hand, if SiPMs are connected in series, the increased impedance would reduce the signal amplitude, which will also increase the impact of electronic noise and affects the time performance. Third, the DCR increases linearly with the SiPM area on a single channel. For instance, the DCR for a 7.3 cm^2 SiPM will reach 36 Mcps at room temperature.

To overcome these challenges, our current design involves the following two steps. Step one, we will combine multiple SiPMs into one channel through serial and parallel connection [8]. The combination of series and parallel configurations helps mitigate the influence of capacitance and impedance to some extent. In step two, we need to secondarily superimpose and amplify the integrated channels into a single channel. For instance, if we combine 9 SiPMs into one channel at step one, and secondarily superimpose 9 of these channels at step two, the total power consumption of a SiPM array, which consists of 81 SiPMs, will be about 1W. As for the DCR, it will decrease by approximately one order of magnitude at 2 °C, which is about 4 Mcps.

To evaluate the time performance, we conducted resolution measurements using the Pilas PIL040-FS picosecond laser to determine the SPTR of an individual SiPM and a 6-piece SiPM array, as shown in Fig. 5. The laser operates at a wavelength of 405 nm and has an excellent pulse width of approximately 45 ps. Using the synchronization signal from the laser as the trigger time reference for photon arrival time, which has a timing jitter of less than 3 ps, we measured the trigger time distribution at a single photon level, as shown in Fig. 5. The trigger time is defined as the moment when the voltage of the waveform reaches a fixed threshold, which in this case is 5 mV. The full width at half maximum (FWHM) of this distribution at 1 photoelectron (PE) represents the SPTR, which in this instance was 244 ps. For multiple PE, the trigger time shifts earlier, which is mainly because the waveform rises faster and requires less time to reach the threshold. We also evaluated the SPTR of a 6-piece SiPM array, yielding a result of 436 ps at an overvoltage of 3V. This measured SPTR is subject to the influence of electronic noise, suggesting that feasible improvements could be achieved in future measurement through increasing the bandwidth and magnification of the front-end amplifier circuit [9].

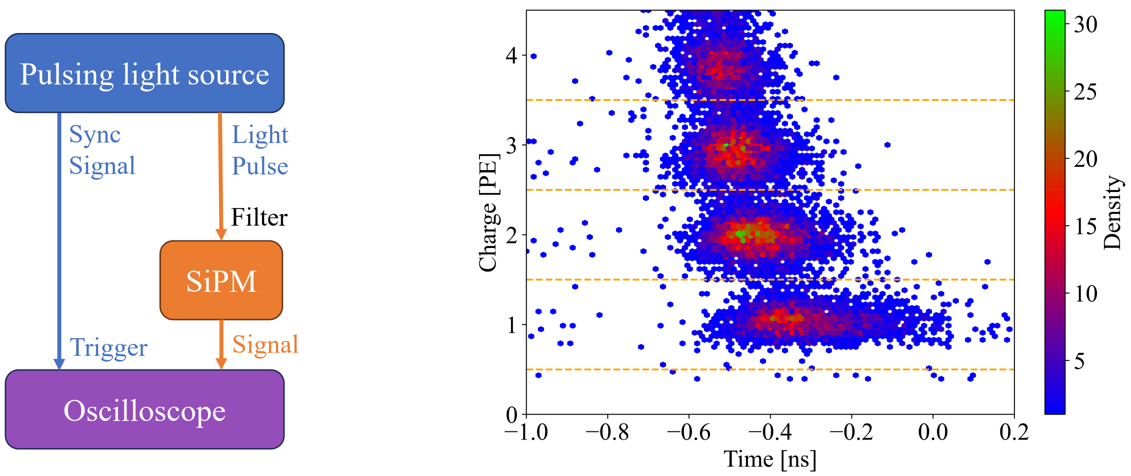

Figure 5: Left: the schematic that illustrates the setup of the SPTR measurement. Right: the distribution of charge versus trigger time at a single photon level for a single SiPM.

3.1 Discussions

The front-end readout of the SiPM is currently in the research and development phase. Future efforts will be dedicated to expanding the array size, enhancing the accuracy of time measurement, and evaluating performance at low-temperature conditions.

The introduction of SiPM signifies a considerable advancement in hDOM design. However, due to their higher dark count rate in comparison to PMTs, SiPMs can increase the rate of false triggers stemming from the random coincidence of dark noise. To address this issue, our proposed data acquisition scheme uses multiple PMT signals as the hDOM trigger and calculates the actual photon hit time by subtracting the PMT transit time difference. This approach capitalizes on the larger photosensitive area of the PMTs, while the SiPMs are used to ascertain a more accurate trigger time that reflects the arrival time of external photons.

4. Summary

In these proceedings, we provide an initial report on the hardware design progress of hDOM, focusing on both mechanical and electronic aspects. From a mechanical standpoint, our work to date encompasses the overall layout of hDOM, the creation of a 3D-printed bracket, and the development of mounting mechanisms for PMTs and SiPM arrays. For electronics, we have conducted preliminary research on the front-end readout of SiPMs.

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