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A New Underwater Optical Modem based on Highly Sensitive Silicon Photomultipliers

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Abstract :

Silicon Photomultipliers (SiPMs) have recently been recognized as an interesting alternative to photomultiplier tubes (PMTs) thanks to their high sensitivity and time resolution. They can closely approach quantum-limited sensitivity in the detection of weak optical signals. Ifremer (French Research Institute for Exploitation of the Sea) and Institut Fresnel research lab have been investigating appropriate alternative solutions for PMTs in the context of underwater optical communications, and have for the first time used these new photodetector components for signal detection. A novel prototype of an optical modem based on SiPM receivers was realized with support from Osean SAS Co., a French instrumentation company. A number of lab experiments and sea trials in turbid waters and clear open sea were conducted using this modem to evaluate the practical interest of SiPMs. This paper studies the feasibility of using SiPMs for underwater optical communications. It outlines the description of the transmitter and the receiver of the modem prototype, the different techniques used to take advantage of this new technology and solutions to possible practical challenges. It also presents the methodology of the conducted sea trials and the performance evaluations in terms of range and data rate.

Keywords : optical communications, underwater communications, Silicon photomultipliers, photomultiplier tubes

I. INTRODUCTION

High-speed underwater optical communication is well known as an enabling technology with numerous potential applications in a variety of environments from the deep seas to coastal waters. The resurgence in the interest for underwater optical links has been largely driven in the past decade by a rapidly maturing technology mainly at blue/green wavelengths. Seawater exhibits a "window" of decreased absorption in the blue/green region of the visible spectrum, where a number of off-the-shelf light emitting diodes (LEDs) or laser sources and photodetectors are now available.

The optical underwater channel in the "Blue/Green window" provides a close-to-GHz bandwidth with a range up to 15 attenuation lengths (a few meters in turbid waters up to a few 100 meters in clear ocean waters) [1]. However, the performance of optical links is strongly constrained by the optical properties of the channel, specifically absorption and scattering. In clear waters, such as in deep Open Ocean, absorption is the dominant source of channel loss and has its minimum around the blue wavelength. Links operating in these environments are typically characterized as "photon limited" [2]. The link range may be slightly increased with using higher power optical sources and high sensitivity photodetectors. However, these links are ultimately limited by the exponential attenuation of the channel. In turbid waters, such as in the littoral, coastal and near-shore regions, scattering is the dominant source of attenuation and the absorption minimum shifts to the green wavelength. Links operating in these environments are classified as "dispersion limited" [3], [4]. Unlike the photon-limited link, the performance of dispersion-limited links is mainly constrained by pulse broadening, or in other words, inter-symbol interference.

On the transmitter side, LEDs are a popular choice among hardware designers, due to their low cost, size, good performance and ease of use, with emerging trends in this area including also efficiency improvements of high-power LEDs capable of high-speed modulation (up to 10 Mbps typically). While LEDs are mostly used at the transmitter, the choice of photodetector at the receiver remains rather open, especially given the emergence of new devices. In fact, on the receiver end, large-aperture, high-efficiency, high-gain and high-speed photodetectors are desirable. Obviously, achieving all of these in a single device is quite difficult. In this study, we focus on the "photon limited" channels and investigate a rather new photodetector for use in such environments. High-speed photomultiplier tubes (PMTs) with high gain (around 10^6) and large apertures (about 25 mm) seem to be the most suitable choice due to their high sensitivity to very low light intensities. They are, for instance, used in the BlueComm®Sonardyne optical communication system. This product is a quasi-omni directional system allowing 10Mb/s transmission over 100m in clear water according to the provided specifications [5], [6], [7], [8]. However PMTs require a high operating voltage, are easily damaged by ambient light exposure and are rather fragile due to their sensitivity to magnetic fields.

Recently Silicon Photomultipliers (SiPMs) have been recognized as interesting competitive alternatives to PMTs due to their high sensitivity and time resolution and seem to be particularly attractive for photon-limited links. In order to assess the practical interest of these new devices and their limitation within the context of underwater optical communications, Ifremer has undertaken the realization of a

SiPM-based optical modem prototype and its real-field test to evaluate its performances. We first present the operational principle of SiPMs with their benefits and drawbacks, followed by the different techniques used to design the prototype. Afterwards, we present the experimental performance results performed in shallow waters and the comparison with the PMT-based BlueComm200 product of Sonardyne.

II. SiPM Challenges

SiPMs are well recognized as very promising photodetectors thanks to their unique photon detection capability and exceptional single photon time resolution. As such, this new generation of photodetectors provides a very high receiver sensitivity and shows numerous advantages as compared to the rather traditional devices such as PMTs or avalanche photodiodes (APDs). In particular, SiPMs present high gain, low operating voltage, compactness, convenience for integration, insensitivity to magnetic fields and important potential as low cost components (as it requires following the standard CMOS fabrication process) [9], [10]. All these facts make SiPMs very interesting devices for photon detection applications where high frequency and very low intensity detection are among the required features. In Table I, we have compared the main characteristics of the four different photodetectors types, i.e., PIN, APD, PMT and SiPM [11], [12].

TABLE I.

Comparative Characteristics of Photodetectors

Parameters	***PIN***	***APD***	***PMT***	***SiPM***
Gain	1	~10^2	~10^6	~10^6
Bias Voltage	Low	High	High	Low
T°C sensitivity	Low	High	Low	High
Spectral Range	Red	Red	Blue/UV	Blue
Electronics	Complex	Complex	Simple	Simple
Sensitivity to Magnetic Fields	No	No	Yes	No
Noise Level	Low	Medium	Low	Medium
Mechanical Robustness	High	Medium	Low	High
Form factor	Compact	Compact	Bulky	Compact

Basically, a SiPM is a matrix of APDs working in Geiger mode. In this mode, the operating bias is several volts above the breakdown voltage. Each "cell" or "pixel" is commonly called a single-photon avalanche diode (SPAD). When the SPAD pixels receive photons, the photo-generated carriers trigger avalanche breakdowns, where the photoelectric conversion gain can reach 10^5-10^7. Usually, a resistor is in charge of collapsing the avalanche process in each SPAD, a short time after it starts; it is called the "quenching device" and the SPAD is called as passively quenched. Since all cells in the SiPM are connected to a common metallic grid, the total photocurrent is proportional to the number of fired cells. The typical response of the SiPM to an incoming light pulse is a very fast rising edge (avalanche is happening) followed by a slow downfall (avalanche being quenched) [13], [14]. However, for long light pulses the output response of a SiPM shows a rather complicated transient behavior; typically in the form of an exponential decay with a characteristic time inversely proportional to the peak amplitude [14]. In fact, the detection of an arbitrary waveform optical signal (i.e., reconstructing the temporal form of the received signal after photo-detection) when using a SiPM appears to be specially challenging [15]. Moreover, during the quenching cycle, the SiPM is unresponsive; which practically limits the counting rate to a few Mbps [14].

In fact, the detection of short and low-intensity pulses of nanosecond time scale appears to be the best suited for SiPM applications because for such signals, most of the above-mentioned SiPM drawbacks have rather limited effect on the amplitude and time resolution of the detected signal [16], [17]. So, for the underwater optical communication application, we have implemented a specific technology in order to use the SiPM in the most effective way. We have partially resolved these challenges in the design of our prototype described below, by using very short pulse modulation and the implementation of an active automatic gain control (AGC).

III. Prototype Design and Testing

Ifremer's Underwater Systems Unit has recently developed with the support from Osean Co. (French Instrumentation Company) an underwater optical modem based on SiPM technology. The receiver is designed as an antenna with 8 fast, blue-sensitive SiPM "sensors". Each sensor has a 36 mm^2 active area providing a wider than 30° field of view (FOV). The receiver array is integrated into a cylindrical housing with a spherical glass BK7 dome, allowing an omnidirectional FOV.

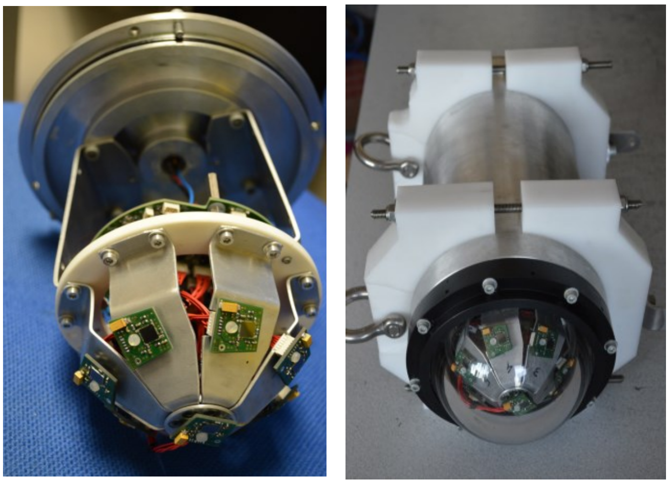

Fig.1. SiPM-based Receiver antenna with its housing

After this front-end system, an FPGA-based demodulator sends the decoded signal to an ARM embedded Ethernet board (see Fig.1). For the design of this prototype, we have reused a number of parts from previous designs, such as dome, housing, underwater connector etc… The prototype is hence not optimized and could be made, of course, more compact. The signal output of the antenna is amplified with a high gain amplifier followed by a threshold comparator.

The transmitter is composed of 120 fast blue LEDs arranged on a circular epoxy board, with a fast high power amplifier. The emitting beam angle is around 120°. The Ethernet signal input is encoded by the same FPGA/ARM boards as at the receiver side (see Fig.2).

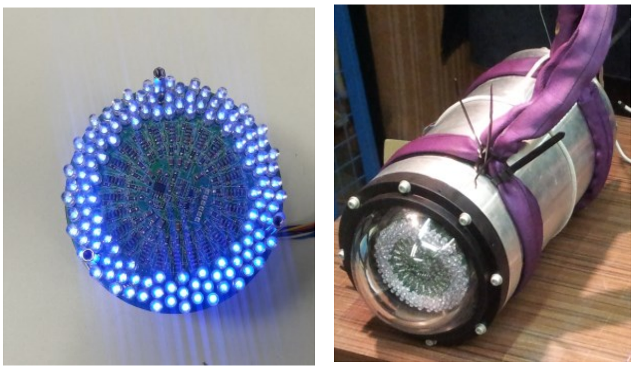

Fig.2. LED-based Transmitter with its housing

Notice that, at this stage of development, for the sake of simplicity, only one SiPM is effectively used for signal detection. Also, the link is unidirectional, without any forward error correction, and the Ethernet protocol is based on a simple Manchester OOK modulation. The optical link transfer protocol at the current state is rather simple as it has not been the aim of this project. More sophisticated and efficient transmission protocols should be envisaged in the final product development. Note that although our current prototype has somehow limited functionalities, they are nevertheless sufficient for evaluating the link performance, especially in terms of range and data rate, and for comparing them with that of a PMT-based transceiver. Indeed, once again, our goal has been to elucidate the practical interest of the SiPM technology, rather than developing an operational modem with all the network layers implemented.

IV. Benchmarking Test

During 2015-2016, with the support of Total Company, Ifremer performed a benchmark of the SiPM and PMT photodetectors technologies in relatively shallow waters. For the former, we used Ifremer's SiPM-based prototype, and for the latter, the BlueComm200 modem (from Sonardyne®). Tests were conducted on different dates with different deployment systems, but under similar conditions relative to the environment ambient light and water quality.

Ifremer's hybrid ROV (Remote operating vehicle) Vortex was deployed as a mobile platform, with the transmitter (see Fig.3) mounted on it. The Vortex ROV is commonly used for demonstration and testing missions. Equipped with a 3.8kWh battery and INU (Inertial Navigation Unit), Vortex could operate remotely via a WiFi link for over 4 hours. The WiFi link is provided by a tethered buoy which floats on the surface as Vortex dives. The transmitter module was mounted horizontally on starboard side of Vortex with clamps (see Fig.3).

Fig.3. Ifremer's transmitter prototype integrated on Vortex

Vortex was deployed from the transmitter RIB (Rigid-hulled Inflatable Boat) thanks to a very efficient crane installed on the RIB (see Fig.4).

Fig.4. Vortex's Deployment with RIB

The receiver module was fixed on a frame from another RIB. This vessel is equipped with WiFi connection, GPS, and Octans INU (from Ixsea®). All the measurements were performed in this configuration (with GPS, INU), with Vortex moving away from the receiver's vessel (see Fig.5). The turbidity (attenuation of the Blue light 460nm) was measured using a C-Star transmissometer (from WetLabs®). Vortex was programmed to realize profiles parallel to the receiver (see Fig.6).

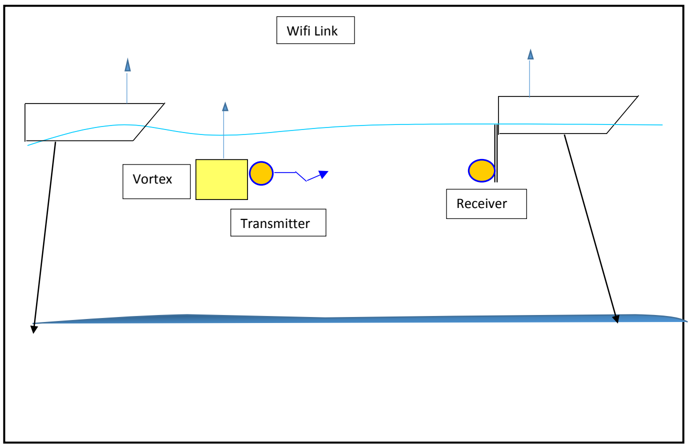

Fig.5. Ifremer's SiPM-based prototype system setup

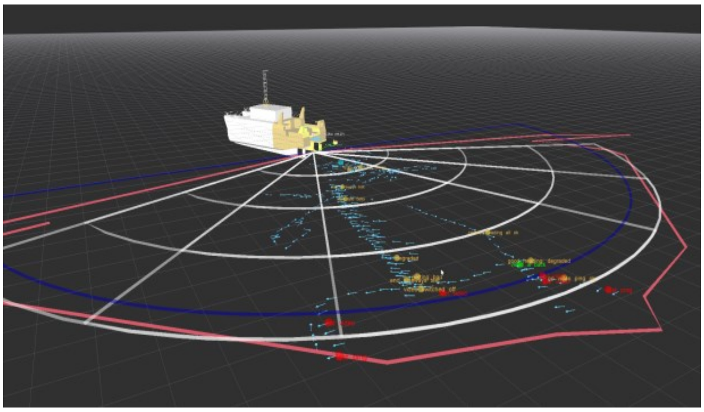

Fig.6. Vortex's dive with marker points and comments on the link quality

The goal of these series of tests was to evaluate the performance of the two modems in the real-field mobile-to-fixed platform link configuration, where Vortex had the role of the mobile platform and a fixed modem was used on a ship at anchor. Vortex would be at sea in AUV (Autonomous Underwater Vehicle) mode, with a WiFi buoy at surface to control it and to get data in real time on the ship. As the optical modems are designed to work with little to no ambient light sources, all tests were carried out in the open sea during night in order to simulate as far as practically possible the darkness of deep waters in different locations in open sea, with different water qualities (see Fig.7). However, at the shallow depth where the trials were conducted (around just 2.8m below the surface), the ambient light from moon and the city (just a few miles away), effectively limited the attainable range performance.

Tests with this prototype concerned the transmission of a series of images. With the positioning of Vortex (dead reckoning, GPS) and the GPS positioning of the RIB emitter, we could calculate the distance between the two modems and hence evaluate the range. We also got the heading with the INU. All this information was processed in real time, logged and time stamped with the other data.

Concerning the trials using the BlueComm200 modem, carried out in 2015, we mounted one modem to a temporary over-the-side pole deployed from the stern of "Europe", Ifremer's 29 meter coastal research catamaran [18]. The second modem was installed on Vortex. The test procedures were the same as described above. We conducted these real-field trials in open sea, with different water qualities from Jerlov I (corresponding to deep clear Ocean waters), up to Jerlov 5 (corresponding to turbid coastal waters) [19], [20]. Tests with BlueComm 200 used Vortex's onboard camera to constantly stream video.

Fig.7. First tests in the harbor with Ifremer's SiPM-based prototype

V. Sea Trial Results

As a matter of fact, the performances of the two optical underwater modems are not directly comparable. BlueComm 200 is already a product commercialized by Sonardyne, whereas Ifremer's SiPM-based modem is just a prototype with less functionality that was developed in order to evaluate the efficacy of the SiPM technology. Nevertheless, these sea trials that were performed under similar conditions with similar water quality and same link configurations (fixed-to-fixed and fixed-to-mobile platforms), allowed us to conclude on the performances of each modem. As data rates of the currently developed SiPM-based modem are in the range of 125kbps to 3Mbps, Table II summarizes the performances in range at around 3Mbps.

TABLE II.

Range performances in the shallow waters tests

Modem	Jerlov Classification	Water quality in NTU	Max range @Mbps
BlueComm200	Jerlov 5	**4**	**24m@2.5Mbps**
Ifremer's SiPM	Jerlov 5	**4**	**17m@3Mbps**
BlueComm200	Jerlov I	**0.32**	**80m@2.5Mbps**
Ifremer's SiPM	Jerlov I	**0.32**	**60m@3Mbps**

Furthermore, the receiver FOVs of the Bluecomm200 and SiPM-based modems were measured as around 90° and 60°, respectively (remember that in these tests, only one of the SiPM sensors was used for signal detection). Generally we can conclude that SiPM technology has performances in range 25% below PMT technology (with this simple modulation used).

As we can see from Table II results, the BlueComm200 modem outperforms more or less the Ifremer prototype, which can be justified given the lower noise level of PMTs and their higher sensitivity, as compared with SiPMs. However, the advantages of SiPMs to PMTs in terms of practical implementation and operational facility are undeniable, as outlined previously in this paper. We hope that by improving the design of our prototype (in particular by enabling the use of all eight sensors) we can improve the modem performance in terms of range and FOV.

VI. Numerical Simulation Results

Some numerical simulations have been processed beforehand with Institut Fresnel, in order to study the performance of a SiPM-based receivers. To make a fair comparison between SiPM and PMT, we assumed that all components have equal physical areas. The PMT gain was set to 10^7 and the SiPM characteristics correspond to the component used in the prototype (i.e. MicroSB 30035 from SensL [10]). We have shown the BER results for the case of uncoded OOK modulation in Fig.8. Two cases of clear ocean (Jerlov I) and turbid coastal waters (Jerlov 5) are considered, as for the experimental tests. The diffuse attenuation coefficient [21] for these water types is 0.08 and 0.5 m^{-1}, respectively. These confirm the previously presented experimental results. We notice a better performance for the PMT-based receiver.

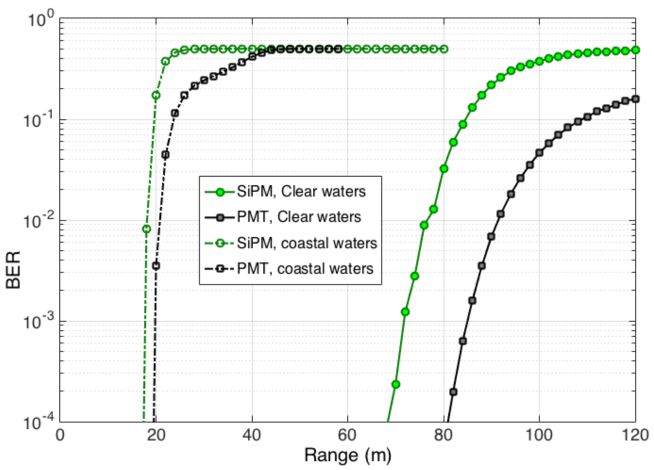

Fig.8. BER performance as a function of link range for PMT and SiPM. uncoded OOK modulation at 1Mbps

VII. SUMMARY

In this study we showed the practical interest of SiPMs as interesting and promising photodetectors for underwater optical communications. SiPMs allow achieving link performances far above those of APDs. Nevertheless, although they are as sensitive as PMTs, current SiPMs cannot reach the same range and data rate as the PMT counterparts. Indeed, arbitrary waveform signal detection is a very challenging issue for the currently existing SiPM technology because of high distortion of the output pulse shape at high intensities.

However, this issue will hopefully be resolved with a new generation of high density, fast recovery, fast response, low crosstalk, and low after pulsing SiPMs, which are under ongoing development. Considerable improvement in the link performance can also be achieved, for instance, through implementing new optimized modulation schemes to increase the data rate and link distance, or by adding micro lenses in front of the SiPMs to concentrate light on their photosensitive area. Finally, the ability of easily arranging multiple SiPMs to form an antenna, in order to obtain a large FOV receiver is a very promising feature of this technology.

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