# Underwater optical wireless sensor network for real-time underwater environmental monitoring

| | |
|---|---|
| Item Type | Conference Paper |
| Authors | Kong, Meiwei; Guo, Yujian; Sait, Mohammed; Alkhazragi, Omar; Kang, Chun Hong; Ng, Tien Khee; Ooi, Boon S. |
| Citation | Kong, M., Guo, Y., Sait, M., Alkhazragi, O., Kang, C. H., Ng, T. K., & Ooi, B. S. (2022). Underwater optical wireless sensor network for real-time underwater environmental monitoring. Next-Generation Optical Communication: Components, Sub-Systems, and Systems XI. https://doi.org/10.1117/12.2607942 |
| Eprint version | Post-print |
| DOI | 10.1117/12.2607942 |
| Publisher | SPIE |
| Rights | Archived with thanks to SPIE |
| Download date | 01/10/2023 03:12:44 |
| Link to Item | http://hdl.handle.net/10754/675732 |

# Underwater optical wireless sensor network for real-time underwater environmental monitoring

Meiwei Kong, Yujian Guo, Mohammed Sait, Omar Alkhazragi, Chun Hong Kang, Tien Khee Ng, Boon S. Ooi*
Photonics Laboratory, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia
*boon.ooi@kaust.edu.sa

## ABSTRACT

With the growing number of underwater vehicles and devices used for marine environmental monitoring, there is an urgent need for real-time and high-speed underwater wireless communication technologies to transmit huge amounts of data. This poses great challenges to conventional underwater acoustic communication technology due to its low bandwidth and high latency. Therefore, underwater wireless optical communication with high bandwidth and low latency has become a promising technology. To this end, we develop the first underwater optical wireless sensor network prototype in this work. It consists of two sensor nodes and an optical hub. There is a transceiver circuit, a pH sensor, and an integrated temperature, salinity, and conductivity sensor in the sensor nodes enabling real-time underwater environmental monitoring. There are four transceivers facing four sides in the optical hub to implement bi-directional optical wireless communication with the sensor nodes. In a laboratory testbed and a field trial conducted in an outdoor diving pool, 100% packet success rates are achieved between the optical hub and the sensor nodes at a transmission distance of 60 cm. In the field trial, one of the sensor nodes is placed 60 cm away from the optical hub for real-time underwater environmental monitoring. The other sensor node is mounted on a remotely operated vehicle to collect underwater environmental information. This prototype shows great potential in future underwater mobile sensor networks and the underwater Internet of Things.

**Keywords:** Underwater optical wireless sensor network, real-time underwater environmental monitoring, underwater vehicles and devices

## 1. INTRODUCTION

The ocean is an important regulator of global climate and a treasure house of natural resources. Nowadays, to relieve the global environmental and resource crisis, the world has set off an upsurge in marine environmental monitoring, such as coral reef monitoring, fishery monitoring, and subsea oil and gas pipeline inspection. In this context, human's demand for marine information is moving from static to dynamic, from delayed to real-time and instant, and from rough to accurate and complete. Satellite remote sensing technology is an effective means to obtain marine information. It can provide large-scale, all-day, and all-weather marine environmental monitoring information, but it has a relatively poor spatial resolution [1]. The monitoring methods based on stationary platforms, such as oceanographic moorings, benthic landers, and cabled ocean observatories, can provide long-term, in-situ, and high-precision marine information, however, they have a small spatial scale [2]. In recent years, more and more mobile platforms, such as underwater gliders, remotely-operated vehicles (ROVs), and autonomous underwater vehicles, are being used in marine environmental monitoring to enlarge the spatial scale of the stationary platforms [3]. Underwater acoustic communication-based underwater wireless sensor networks (UWSNs) are an enabling communication technology to implement three-dimensional ocean monitoring. With the increasing demand for real-time, high-speed, and efficient UWSNs, the drawbacks of traditional underwater acoustic communication are gradually exposed, such as the high latency, low data rate, and low efficiency due to the low propagation speed (1500 m/s) and limited bandwidth (~kHz) of acoustic waves [4]. Moreover, if the underwater acoustic communication technology is widely used in underwater space as the most important means of wireless communication in the future, it will undoubtedly affect marine organisms that rely on auditory or radar (sonar) systems to prey [5].

The discovery of the “optical transmission window” of 450–550 nm in the year of 1963 brought a new idea to the development of underwater wireless communication technologies [6]. Even though light waves cannot transmit long distances (up to ~km) like acoustic waves, it is preferable for real-time, high-speed (up to ~Gb/s), and short-distance (up to ~100 m) transmission thanks to its high bandwidth and low latency [7]. Nowadays, the race for the development of the underwater wireless optical communication (UWOC) technologies has begun all over the world. To achieve higher data rate and longer transmission distance for point-to-point UWOC technology, various light sources, photodetectors, modulation and multiplexing schemes, equalization algorithms, and underwater channels have been explored extensively [8]. With the continuous technological breakthroughs, field trials in various underwater environments, such as indoor swimming pool, outdoor diving pool, dock, harbor, lake, river, and ocean, have been conducted [9-11]. Up to now, there have been a few commercial underwater optical modems developed by Sonardyne and Divecomm. For the next generation of smart UWOC system development, one could expect underwater optical wireless sensor networks to be implemented for real-time marine environmental monitoring. However, there are limited theoretical or simulation works on the underwater optical wireless sensor networks [3]. Therefore, there is a need for experimental research to be conducted in this area.

In this paper, we develop the first underwater optical wireless sensor network prototype. It consists of an optical hub, two sensor nodes, and a base station. The optical hub and the sensor nodes can implement bidirectional communication through UWOC technology. The two sensor nodes can also communicate with each other through the optical hub. Moreover, the optical hub and the base station can implement bidirectional communication through an Ethernet cable. Thus, one can remotely access the data uploaded by the sensor nodes in the optical hub and send instructions (e.g., sampling interval) and upgrade files to the sensor nodes in real time through the optical hub at the base station. In a laboratory testbed, both of the sensor nodes are placed 60 cm away from the optical hub. 100% packet success rates are achieved, which indicates the good communication performance of the network system. To further demonstrate the practicality of the network system, a field trial is conducted in an outdoor diving pool. One of the sensor nodes is placed 60 cm away from the optical hub for real-time underwater environmental monitoring. An ROV is used to carry the other sensor node to collect underwater environmental information and then return back to the optical hub for data upload. This prototype shows great potential in future underwater mobile sensor networks and the underwater Internet of Things.

# 2. EXPERIMENTAL SETUP AND RESULTS

## 2.1 Experiment in the laboratory testbed

We first studied the communication performance of the underwater optical wireless sensor network prototype in the laboratory testbed. Figure 1(a) shows the experimental scene of the underwater optical wireless sensor network, which includes an optical hub (see Fig. 1(b)), Sensor Node 2 (see Fig. 1(c)), Sensor Node 3, and a base station. Sensor Node 2 and Sensor Node 3 were placed 60 cm away from the optical hub. The base station was connected to the optical hub through an Ethernet cable.

The optical hub is composed of a system on chip (SoC) circuit and four transceiver circuits. The SoC circuit is used for on-off keying (OOK) modulation and demodulation. The data rate of the OOK signals is 1.5 Mb/s, which is sufficient to transmit the regularly collected temperature, salinity, conductivity, and pH information. Four transceiver circuits of the optical hub facing four directions are used for bidirectional communication with the transceiver circuit of the sensor node, where time division multiple access enables them to communicate at different time slots. At the transmitter side, a driver is used to superimpose OOK signals output from the SoC onto an LED. A lens is used in front of the LED to control the beam divergence. At the receiver side, another lens is used in front of a photodiode (PD) to focus the light. After detection by the PD, the received OOK signals are amplified by an operational amplifier (OPA) and then the noise is removed by a low-pass filter (LPF).

The sensor node is composed of a sensor hub and a transceiver circuit. The sensor hub is composed of a coprocessor, an organic light-emitting diode (OLED) screen, a real-time clock (RTC) chip, a SD card, a pH sensor, and an integrated temperature, salinity, and conductivity sensor. The OLED screen is used to display the time, temperature, salinity, conductivity, pH, and version of the sensor node. The RTC chip is used to synchronize the time of the sensor node with that of the base station. The SD card is used to store the collected temperature, salinity, conductivity and pH information. The transceiver circuit in the sensor node is identical to the one in the optical hub.

In the design process of the underwater optical wireless sensor network prototype, we did not simply consider the physical layer to pursue high data rate and long distance but comprehensively considered Open Systems Interconnection layers and many practical application factors. For example, as it is difficult to charge or replace batteries for underwater optical wireless sensor networks, we designed the optical hub and sensor node to only need five 18650 batteries (each with a capacity of 3400 mAh), which is enough to power them up for around 5 hours continuously. Moreover, considering the transmission distance and the link alignment issues, we designed the divergence angle of the LED to 34 degrees with the help of lenses.

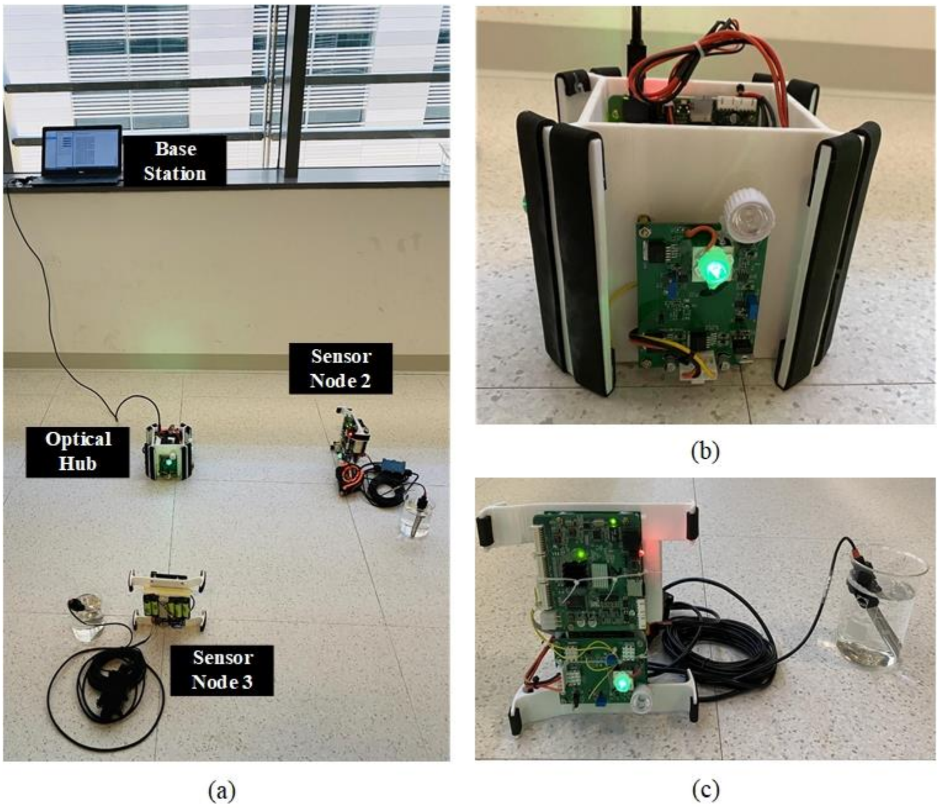
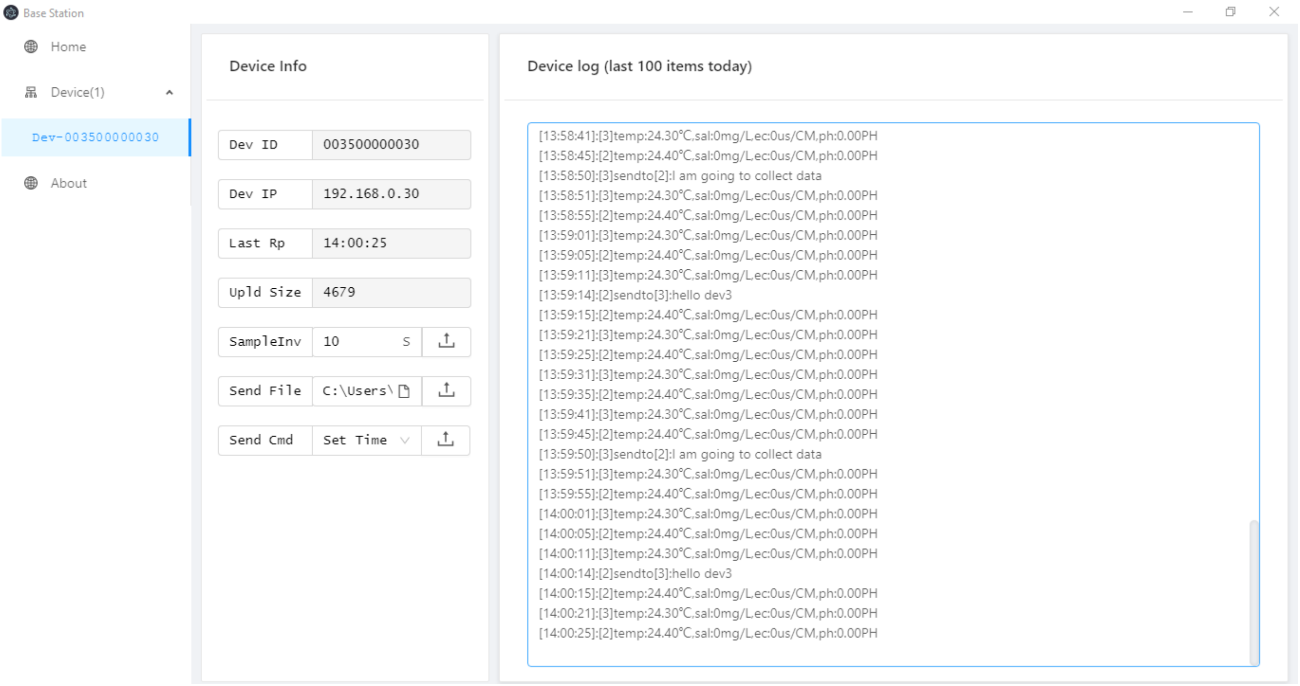


Figure 1. (a) Experimental scene of the underwater optical wireless sensor network, (b) optical hub, and (c) Sensor Node 2.



Dev ID 003500000030

Dev IP 192.168.0.30

Last Rp 14:00:25

Upld Size 4679

SampleInv 10 S

Send File C:\Users\

Send Cmd Set Time

```
[13:58:41]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:58:45]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:58:50]:[3]sendto[2]:I am going to collect data
[13:58:51]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:58:55]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:01]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:05]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:11]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:14]:[2]sendto[3]:hello dev3
[13:59:15]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:21]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:25]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:31]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:35]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:41]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:45]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:50]:[3]sendto[2]:I am going to collect data
[13:59:51]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[13:59:55]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[14:00:01]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[14:00:05]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[14:00:11]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[14:00:14]:[2]sendto[3]:hello dev3
[14:00:15]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[14:00:21]:[3]temp:24.30℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
[14:00:25]:[2]temp:24.40℃,sal:0mg/L,ec:0us/CM,ph:0.00PH
```

Figure 2. Control interface of the device.

Figure 2 shows the control interface of the base station through which we can set the sampling interval, send commands or updated files, and synchronize the time of the sensor nodes. We can see that Sensor Node 2 and Sensor Node 3 can upload data to the optical hub at different time slots. Moreover, Sensor Node 2 and Sensor Node 3 can communicate with each other through the optical hub over a transmission distance of 0.6 m. As shown in Fig. 2, Sensor Node 2 said “hello dev3” to Sensor Node 3, and Sensor Node 3 replied “I am going to collect data”. In the experiment, the transmitted packets, missed packets, and packet success rate from the sensor nodes to the optical hub were 200, 0, 100%, respectively. It indicates the reliable communication performance of the network system.

### 2.2 Experiment in the outdoor diving pool

We then studied the feasibility of the underwater optical wireless sensor network prototype in the outdoor diving pool. Figure 3 shows the experimental scene. Sensor node 2 was placed 60 cm away from the optical hub. Sensor node 3 was mounted on an ROV to collect data. The transmitted packets, missed packets, and packet success rate were 200, 0, 100%, respectively, which demonstrated the robustness of the network system.

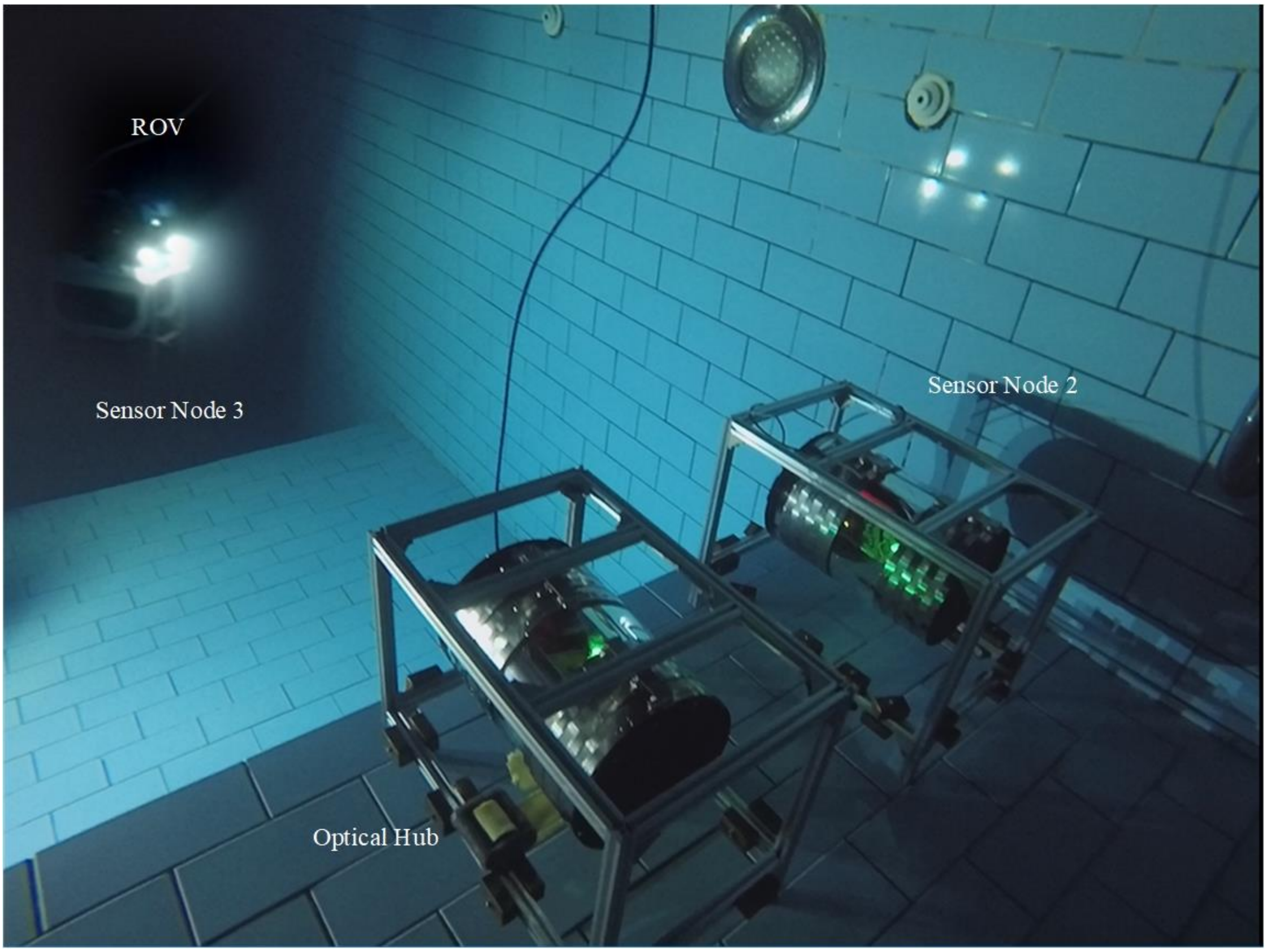


Figure 3. Experimental scene of the underwater optical wireless sensor network in the outdoor diving pool.

## 3. CONCLUSIONS

In this work, we developed an underwater optical wireless sensor network prototype. An integrated temperature, salinity, and conductivity sensor and a pH sensor in the sensor nodes can implement real-time underwater environmental monitoring. An optical hub can communicate with multiple sensor nodes at different time slots for data exchange. A base station connected with the optical hub through an Ethernet cable can send commands and updated files to the sensor nodes. This demonstration paves the way for future automatic remote operations in underwater environment. In the laboratory testbed, 100% packet success rates were achieved between the optical hub and the sensor nodes at a transmission distance of 60 cm. In the field trial conducted in an outdoor diving pool, an ROV carried a sensor node to realize mobile monitoring of an underwater environment and data exchange with the optical hub over a 60-cm underwater channel. This shows that the underwater optical wireless sensor network prototype has excellent communication performance in underwater environments. In the future, the data rate can be improved further for real-time underwater video monitoring. The transmission distance can also be improved by employing LED arrays and photodiodes arrays for future long-distance and high-speed UWOC between AUVs/ROVs or between AUVs/ROVs and sensor nodes.

## ACKNOWLEDGEMENTS

This work was supported in part by King Abdullah University of Science and Technology (KAUST) under Grants BAS/1/1614-01-01, KCR/1/2081-01-01, KCR/1/4114-01-01, and GEN/1/6607-01-01 and in part by King Abdulaziz City for Science and Technology under Grant KACST TIC R2-FP-008. We appreciate and acknowledge Water Sports Centre in KAUST for giving the access to the diving pool.

## REFERENCES

[1] Teague J., Allen M.J., Day J.C., and Scott T.B., "A review of current coral monitoring tools/diagnostic methods & introducing a new tool to the coral health toolkit," (Preprint), DOI: 10.20944/preprints202008.0045.v1, submitted: July, 2020.

[2] Marini S., Gjeci N., Govindaraj S., But A., Sportich B., Ottaviani E., Márquez F.P.G., Bernalte Sanchez P.J., Pedersen J., Clausen C.V., and Madricardo F., "ENDURUNS: An integrated and flexible approach for seabed survey through autonomous mobile vehicles," J. Mar. Sci. Eng. 8, 6332020 (2020).

[3] Saeed N., Celik A., Al-Naffouri T.Y., and Alouini M.S., "Underwater optical wireless communications, networking, and localization: A survey," Ad Hoc Netw. 94, 101935 (2019).

[4] Oubei H.M., Shen C., Kammoun A., Zedini E., Park K.H., Sun X., Liu G., Kang C.H., Ng T.K., Alouini M.S., and Ooi B.S., "Light based underwater wireless communications," Jpn. J. Appl. Phys. 57, 08PA06 (2018).

[5] Ooi B.S., Kong M., and Ng T.K., "Underwater wireless optical communications: Opportunity, challenges and future prospects commentary on "Recent progress in and perspectives of underwater wireless optical communication"," Prog. Quant. Electron. 73, 100275 (2020).

[6] Duntley S.Q., "Light in the sea", JOSA 53(2), 214-233 (1963).

[7] Sun X., Kang C.H., Kong M., Alkhazragi O., Guo Y., Ouhssain M., Weng Y., Jones B.H., Ng T.K., and Ooi B.S., "A review on practical considerations and solutions in underwater wireless optical communication," J. Lightwave Technol. 38(2), pp. 421-431 (2020).

[8] Zhu S., Chen X., Liu X., Zhang G., and Tian P., "Recent progress in and perspectives of underwater wireless optical communication," Prog. Quant. Electron. 73, 100274 (2020).

[9] Pontbriand C., Farr N., Hansen J., Kinsey J.C., Pelletier L.P., Ware J., and Fourie D., "Wireless data harvesting using the AUV Sentry and WHOI optical modem," Proc. OCEANS 2015-MTS/IEEE Washington, 1-6 (2015).

[10] Kong M., Lin J., Guo Y., Sun X., Sait M., Alkhazragi O., Kang C.H., Holguin-Lerma J.A., Kheireddine M., Ouhssain M., Jones B.H., Ng T.K., and Ooi B.S., "AquaE-lite hybrid-solar-cell receiver-modality for energy-autonomous terrestrial and underwater Internet-of-Things," IEEE Photon. J. 12(4), 7904713 (2020).

[11] Hamilton S.A., DeVoe C.E., Fletcher A.S., Gaschits I.D., Hakimi F., Hardy N.D., Howe T., Mittleman N., Rao H.G., Scheinbart M.S., and Yarnall T.M., "Undersea narrow-beam optical communications field demonstration," Proc. Ocean Sensing and Monitoring IX, International Society for Optics and Photonics, 10186, 1018606 (2017).