Remote Control of Underwater Drone by Fiber-Coupled Underwater Optical Wireless Communication

Takao Sawa
MarE3
JAMSTEC
Yokosuka, Japan
sawa@jamstec.go.jp

keiko Sato
Startup Incubation Center
Shimadzu Corp.
Kyoto, Japan
sato.keiko.o6d@shimadzu.co.jp

Kensuke Watari
Offshore Technologies
Yokohama, Japan
watarik@offshore-technologies.com

***Abstract*— In this research, we prototyped an underwater optical wireless communication device that directly transmits and receives optical signals at the end of an optical fiber, and try to remotely control an underwater drone by the device. Since the area of the optical fiber end face is very small, lights emitted by multiple laser diodes are guided into one optical fiber with lens to brighten the light from the end. In addition, a plastic optical fiber with a large core diameter is used for receiving many optical signals in the device. First, the profile of the transmission beam and receiving beam, and the difference in output intensity from each port of the beam combiner were confirmed. Based on these results, the orientation of the end of the optical fibers are adjusted and installed on the bottom of the pool. In the remote control of the underwater drone equipped with a small optical wireless communication device, it was possible to operate with the poolside controller while checking the image of the onboard camera via optical wireless communication. The area where the drone could be controlled was almost the entire pool.**

Keywords—UOWC, optical fiber, underwater, wireless communication, drone

I. Introduction

Conventionally, acoustic waves have been used for underwater wireless communication, and it performs communication over a distance of 10 km. However, since its communication speed is around 10 kbps, it has been used in a limited way such as transmission of command and telemetry. Electro-magnetic waves are extremely attenuated in water, and reach only around 10 cm in water in the 2.4 GHz band which is used by mobile phones. Therefore, underwater optical wireless communication (UOWC) has been attracting attention as a High speed underwater wireless communication technology.

Since the 1960s, when lasers were developed, research on the propagation of light in water and its applications has been conducted. In the 1970s, light propagation characteristics at different wavelengths and water qualities were measured in the pool and the sea to mathematically model the transmission and scattering of light in water [1-2]. The effects of biological substances with luminescence such as chlorophyll were also reported later [3]. The blue light emitting diode (blue LED) became practical elements in the 1990s, which is a suitable light source for UOWC with high power, high speed, low power consumption and compact. In the 2000s, plural UOWC devices were prototyped, and one of it can communicate at 1 Gbps in pool tests [4-7]. In the 2010s, UOWC devices for practical use in the sea were prototyped. The communication speed of 1 Mbps was achieved at a distance of 130 m [8-11]. Currently, it has been commercialized by plural companies [12-14].

UOWC detects blink of light source such as LED and laser diode (LD) at high speed with high sensitivity elements such as photodiodes (PD) and photomultiplier tubes (PMT). ON / OFF keying, which is simple coding, is often used for UOWC. Based on research [15-16] that models seawater as a communication medium and analyzes transient responses, however, optical OFDM technology is applied to UOWC. New research is also underway. Improving communication speed [17-18], improving SN by differential signal [19], wavelength division multiplexing communication [20], research on MIMO [21], communication that directly connects air and water by optical radio while considering the influence of waves [22-23] are tried. There are also several papers summarizing the current status of UOWC [24-26].

The authors have developed a device to measure light attenuation, reflection and scattering in the deep sea [27], and have measured these up to 1,000 m depth around Japan. Based on the results, the prototype UOWC device are made and was installed on a remotely operated vehicle (ROV) and achieved 20 Mbps at a distance of 120 m [28]. This is a high speed that cannot be realized by sound waves, but the communication range of it is short. In addition, the performance is greatly affected by surrounding brightness and the turbidity in water. Making countermeasures against this performance deterioration, we have paid attention to UOWC that emits and receives light by optical fiber.

II. Fiber-Coupled Underwater Optical Wireless Communication Device

A. Basic concept

Sunlight hardly reaches the water at a depth of 200 m. This simply means that the attenuation of light is large in water, and it is also the reason why the communication range of UOWC is short. Therefore, if an optical signal is transmitted through an optical fiber whose attenuation of light is small to where wireless communication is needed, and if the optical signal is emitted from and received into the end of the optical fiber, optical signal can be sent and received on the ground facility away from service area of the wireless communication. No power is required at the service area in the water to send and receive the signals. In addition, splitting and gathering of optical signals is easy, and it realizes flexible directivity of the optical signals. This structure sends optical signals not only with high energy efficiency, but also suppresses interference by unexpected external lights.

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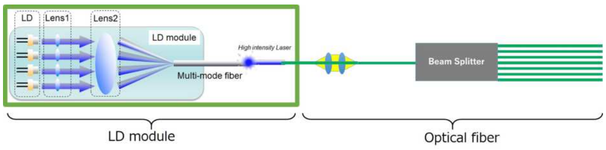

Fig. 1. Beam combiner connected to a fiber-coupled LD module. Lights emitted with Multiple LDs are guided into one optical fiber, and then branched by a beam combiner. There is an advantage that decoupling the LD module and the beam combiner can be done with one underwater optical connector.

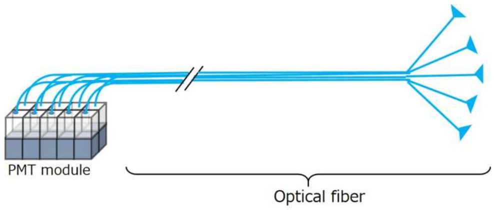

Fig. 2. Optical fibers in the fan-shape are connected to a PMT module. By making the end of the optical fiber fan-shaped, it becomes elements with a wide field of view that enables spatial multiplex communication in future.

We call this UOWC system as a fiber-coupled UOWC. Optical wireless communication that emits and receives light at the end of single-mode optical fibers (SMF) realizes 10 Gbps at about 1 km in communication between fixed devices in the air [29]. However, underwater communication is only proposed as a future concept [30] without equipment.

B. *Structure*

Since it is necessary to use visible light in UOWC, visible light has to pass through optical fibers in fiber-coupled UOWC. The core diameter of SMF is about 10 µm, and that of a multi-mode optical fiber (MMF) is about 50 µm. If the end of the fibers is only faced toward light, the amount of the light guided into the fibers is proportional to the area of the core. It is probably very low. Therefore, as one of the methods to increase the light power, there is a method of condensing light from many LDs with a lens and guiding them into one optical fiber. Since the optical fiber can be easily branched, the condensed light can be distributed to plural optical fibers, and the end of each can be installed at an arbitrary position and direction (Fig. 1). In addition, in order to increase the amount of receiving light, if a plastic optical fiber (POF) with a large core diameter of about 1 mm is used, the amount of receiving light can be improved by about 400 times compared to MMF. However, connecting plural optical fibers to one optical fiber decreases its numerical aperture (NA), that is, the viewing angle of the optical fiber decreases. Therefore, by bundling plural optical fibers and connecting them to the receiving element, it is possible to increase optical signal without decrease of the NA (Fig. 2).

C. *Prototype of fiber-coupled UOWC device and optical wireless underwater drone*

Based on the above discussion, the authors prototyped a fiber-coupled UOWC device. At the same time, we also prototyped an underwater drone that can be remotely operated by UOWC. Figure 3 is a block diagram of the system that remotely controls the drone by the fiber-coupled UOWC device. The fiber-coupled UOWC is divided into an underwater part and a ground part. The ground part encodes the control commands of the drone, converts it to optical signal ,and sends it to the MMF. In addition, the optical signal received by POF is decoded after optical-electric conversion. The LD module (Fig. 4) where lights from multiple LDs are guided into an optical fiber, is used as a light emitting element. MMF is used for the emitting. The PMT arranged in an array (Fig. 5) as a receiving element is used. POF is used for the receiving. In order to install the optical fiber in the water in the appropriate direction and form the desired communication area, the end of the MMF and POF extending from the ground part uses fixtures that can adjust the direction (Fig. 6). The MMF is split into 49 MMF by the optical combiner installed at the middle of MMF in the frame of underwater part. And the POF in a bundle of 7 pieces is connected to the PMT module. There is 12 PMT in the module and 3 bundles are connected to the same PMT, therefore, a total of 252 pieces of POF are in the underwater part.

The optical wireless underwater drone (Fig. 7, Table 2) is based on a conventional type in which a control PC and an underwater drone are connected by wire. It has been converted to an optical wireless, and became cableless by converting power source to built-in battery. The drone is equipped with the MC100DS (tentative name), which is an improved version of the small optical wireless communication device MC100 manufactured by Shimadzu Corporation, which enables communication up to about 40 m (Fig. 8, Table 3).

III. Tests

A. *NA of optical fiber in water*

NA of the optical fiber is a characteristic value based on it in the air. Since the refractive index of air is about 1.00 and it of water is about 1.33, NA in water is show as below:

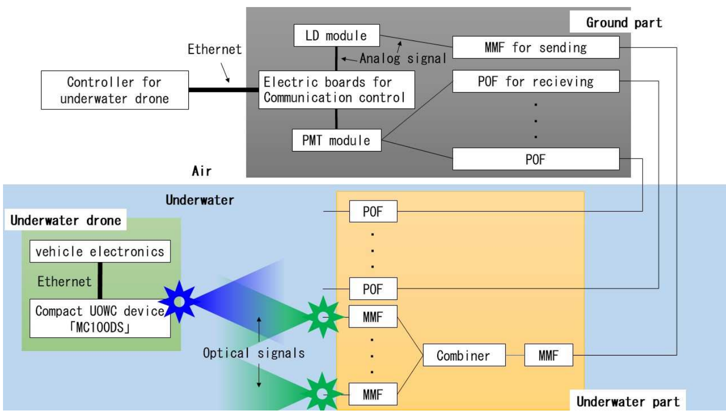

Fig. 3. Remote control system of optical wireless underwater drone by fiber-coupled UOWC device. The drone powered by built-in battery connected to the controller wireless by UOWC.

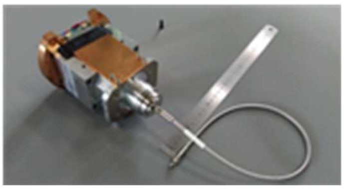

Fig. 4. LD module.

Fig. 5. PMT module.

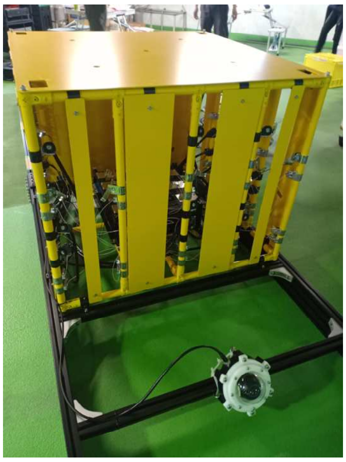

Fig. 6. Underwater part of fiber-coupled UOWC device (optical fiber station part). MMFs and POFs are installed, and these end are faced outside of the yellow frame. A camera (lower right) is installed on the black frame and its video images can be transmitted to the controller of the drone via UOWC.

Fig. 7. Optical wireless underwater drone.

Fig. 8. Small optical wireless communication device for underwater drone "MC100DS (tentative name)".

TABLE I. TABLE TYPE STYLES

Size	Ground part: 51 x 57 x 153 cm Underwater part with frames: 4.0 x 1.0 x 0.9 m
Weight	Ground part: 79 kg Underwater part with frames: 120 kg
Power consumption	545 W
Communication speed	1 Mbps
Communication protocol	TCP or UDP/IP (Ethernet)
Light emitting element	Nichia corp. NDG7K75T Center wavelength: 525 nm Optical output power: 1.0 W
Light receiving elements (12 in total)	Hamamatsu photonics H14600-01 Spectral response: 300-870 nm Max. gain: 2,000,000
Transmitting optical fiber	Nufern MM-S105/125-22A NA: 0.22 Core diameter: 105 μm
Receiving optical fiber	Mitsubishi rayon MH-4001 NA: 0.3 Core diameter: 980 μm
Beam angle	Irradiation: 15 deg. x 36, 40 deg. x 13 Incident: 30 deg. x 36

TABLE II. TABLE TYPE STYLES

Size	488 x 536 x 320 mm
Weight	15 kg
Max. operating depth	50 m
Power consumption	500 W
Observation tools	HD camera x 1 CTD port x 1

TABLE III. TABLE TYPE STYLES

Size	113 dia. x 285 mm
Wieght	3 kg
Max. operating depth	3,500 m
Power consumption	11 W
Communication speed	1 Mbps
Communication range	Up to 50 m
Communication protocol	TCP or UDP/IP (Ethernet)
Light emitting element	Nichia corp. NDB7K75 Center wavelength: 448 nm Optical output power: 3.5 W
Light receiving elements	Hamamatsu photonics H14600-01 Spectral response: 300-870 nm Max. gain: 2,000,000
Bandwidth of optical filter	40 nm
Beam angle	±25 deg.

$$NAw= 1.00 / 1.33 * NA = 0.75 NA \quad (1)$$

Where NAw means NA in water. The NAw becomes smaller than NA, that is, light converges in water become also smaller.

The light emitted from the fiber-coupled UOWC device has been measured by the beam profiler system NanoScan 2s Si / 9/5 (manufactured by Ophir Photonics), and the profile in water has been calculated from the result. Figure 9 shows the result of the calculation. The NAw is expected to be about 0.135, which is smaller than the NA in air, 0.22. However, there was no distortion of the envelope of the graph.

B. Beam splitting by beam combiner

Beam splitters often causes a misalignment and a stray light. In UOWC, Optical signal is high energy density, that is high brightness in short wavelength. It will easily overheat and damage the optical fiber. In this research, a beam combiner, that collects light from an optical fiber originally, was used as a beam splitter by reversing the input / output directions. The beam combiner has a simple structure in which the cross

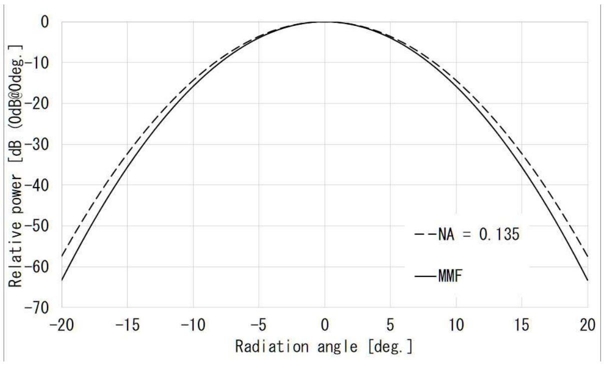

Fig. 9. Beam profile of MMF.

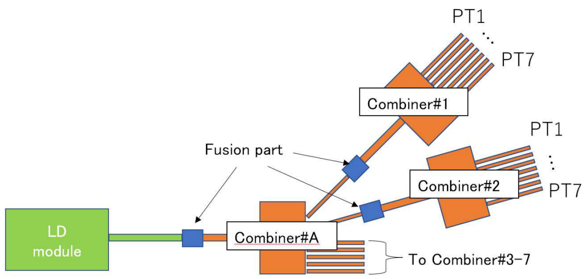

Fig. 10. Splitting of transmitting light by beam combiner.

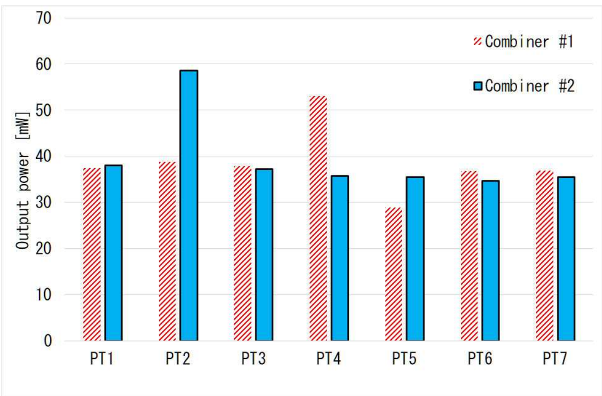

Fig. 11. Optical output power from each PT of # 1 and # 2 combiner.

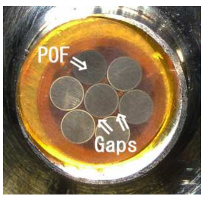

Fig. 12. Enlarged photo of the end of POF (without lens).

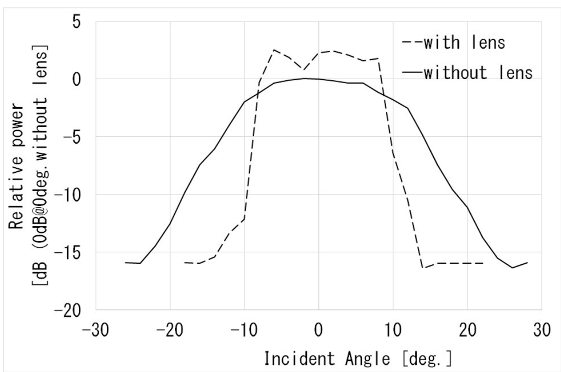

Fig. 13. Beam profile of bundle POF.

section of an optical fiber is divided and connected to multiple optical fibers. Therefore, the energy loss at the connecting point is low.

Figure 10 shows the connection between the LD module and the beam combiners. The light from the LD module branches 7 at beam combiner # A, further branches at combiner # 1 to # 7, and totally branches 49. Figure 11 shows the intensity of light emitted from the branched optical fibers from PT1 to PT7 of both combiners. There is some variation, and differences between combiners # 1 and # 2. In both combiners, one of the seven outputs is high. This is due to the structure of this combiner for 7 into 1. Since six optical fibers are lined up around one optical fiber, the center fiber has different characteristics from others. However, there were no problems other than this structural difference.

C. Light condensing by POF

Figure 12 shows a cross section of seven POFs bundled together to improve the light condensing. Figure 13 shows the beam profiles of the bundled POFs and the beam profile when the Edmund TS high-refractive index hemispherical lens 10 mm is attached to the end of the bundled POFs. The profile is smooth without the lens, however, in the profile with lens, there is low sensitivity at an incident angle larger than ± 10 degrees, and it is high sensitivity at an incident angle smaller than ± 10 degrees. In addition, there is slight variation caused by small gaps between the arranged optical fibers which have no sensitivity.

D. Communication service area

Figure 14 shows the communicable distance and angle range (communication service area) in which communication is possible when the communication light from MC100DS is received by the fiber-coupled UOWC device. The communicable distance Z at the position X where The MC100DS faces toward the fiber-coupled UOWC have been measured in the ocean engineering tank of the Institute of Applied Mechanics, Kyushu University. When the lens is attached in front of the POF end, the distance is extended by about 5 m at X = 0. However, When MC100DS moves in the X direction, the communicable range in the X direction is shortened by about ± 5 m.

E. Remote control of optical wireless underwater drone

We conducted a remote control test of the optical wireless underwater drone using the fiber-coupled UOWC device and MC100DS in the multipurpose pool of Japan Agency for Marine-Earth Science and Technology. Figure 15 shows the arrangement of the underwater part of the fiber-coupled UOWC device on the bottom of the pool. By using 36 MMFs with the irradiation angle of 15 degrees, 7 MMFs with an irradiation angle of 40 degrees, and 36 bundled POFs with an incident angle of 30 degrees in a station block of the underwater part. The communication is possible in all directions near the station block. Furthermore, the optical fiber is extended across the pool so that it can emit and receive optical signals at 3 independent locations in the extension. Two MMFs with an irradiation angle of 40 degrees and a bundled POF with an incident angle of 30 degrees are provided for each of the independent locations. Figure 16 is a schematic diagram of light distribution of the transmitted and the received beams in the pool. The colored area is "service area" of wireless communication. Figure 17 is one scene of the test, with green light emitted from the underwater part and blue transmitted light emitted from MC100DS on the

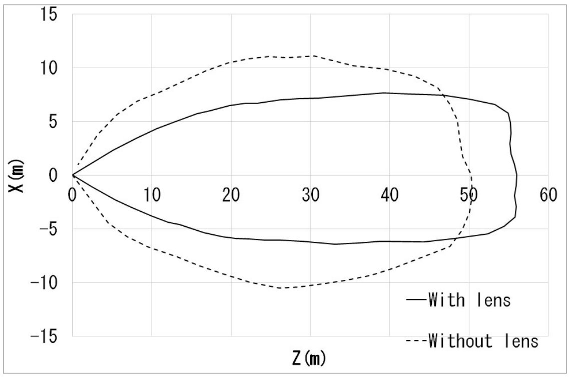

Fig. 15. Predecited communication service area when MC100DS transmits and fiber-coupled UOWC device receives.

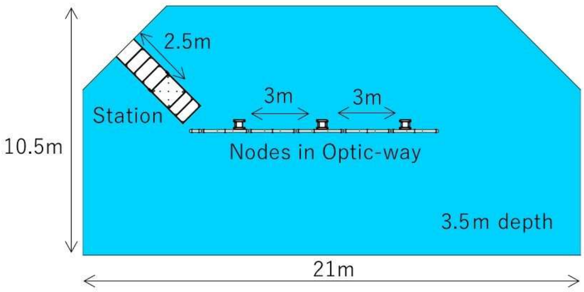

Fig. 16. Underwater part of the fiber-coupled UOWC deployed on the pool bottom.

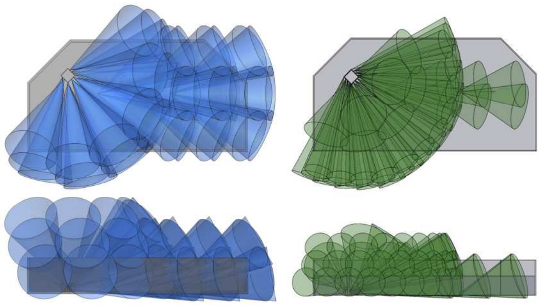
Fig. 17. Schematic diagram of the light distribution and the field of view by the fiber-coupled UOWC device in the pool. The blue cone (in the left) represents the transmission area with the single MMF. The green cone (in the right) represents the receiving area by a the single bundle POF.

underwater drone (however, the drone in this photo is different from the underwater drone in Fig. 7).

In the remote control of the drone by the UOWC, the camera image mounted on the drone was checked by the controller via the ground part on the pool side. The communication was stable even in the noise such as sunlight and ceiling lighting. In addition, the communication was stable when optical signals could not be directly transmitted and received where the optical signals were reflected by the wall, water surface and bottom of the tank. In other words, they are capable in Non Line Of Sight. This suggests that, for example, when operating an optical wireless underwater drone near the quay during the daytime, it may be possible to operate it.

IV. Conclusion

In this research, we prototyped a UOWC device that emits and receives light directly from the end of the optical fiber, measured its characteristics, and confirmed the following.

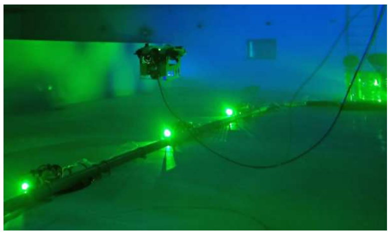
Fig. 14. A photo teken from the observation window on the wall of pool. The green light is emmited from the end of the MMFs on the fiber-coupled UOWC device. A wired underwater drone (at the upper center) monitors comunication stability of the UOWC depending on the position and orientation.

1) The NA of MMF in water was measured, and it was almost the same as the theory.

2) The light was distributed by combiner whose input and output were reversed. Although the amount of light in one of the distributions was high, it was available.

3) 7 POFs were bundled, and a lens was attached in front of the end of it to condense light. The front sensitivity of POFs with a lens became higher than it without lens, however the directivity became narrower.

4) By using a fiber-coupled UOWC device, optical wireless control of the underwater drone was performed while watching underwater via a camera mounted on the drone.

In this research, it was proved that the fiber-coupled UOWC device has practical performance, however, further tests are needed to find out how to set the end of MMF and POF. We are considering spatial multiplex communication, taking advantage of the multi-channel PMT module. Next step, we would like to test the optical wireless underwater drone in the sea, which will lead to the development of cableless operation of ROV, for a new type of drone such as Resident ROV.

Acknowledgment

We would like to express our sincere gratitude to Kazuma Owaki, a project member of the UOWC system in the early days, for his great support including this research. We would also like to thank Mr. Junki Sakamoto of Shimadzu Corporation for his cooperation in the production of the UOWC device, and Mr. Tomoyoshi Ida and Mr. Norihiko Yamato of Optohub Co., Ltd. for their cooperation.

This research was carried out with the support of the Nippon Foundation-Deep Star Collaborative Technology Development Grant Program for Marine Oil and Natural Gas.

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