Ultraviolet-to-blue color-converting scintillating-fibers photoreceiver for 375-nm laser-based underwater wireless optical communication

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Abstract: Underwater wireless optical communication (UWOC) can offer reliable and secure connectivity for enabling future Internet-of-underwater-things (IoUT), owing to its unlicensed spectrum and high transmission speed. However, a critical bottleneck lies in the strict requirement of pointing, acquisition, and tracking (PAT), for effective recovery of modulated optical signals at the receiver end. A large-area, high bandwidth, and wide-angle-of-view photoreceiver is therefore crucial for establishing a high-speed yet reliable communication link under non-directional pointing in a turbulent underwater environment. In this work, we demonstrated a large-area, of up to a few tens of cm², photoreceiver design based on ultraviolet (UV)-to-blue color-converting plastic scintillating fibers, and yet offering high 3-dB bandwidth of up to 86.13 MHz. Tapping on the large modulation bandwidth, we demonstrated a high data rate of 250 Mbps at bit-error ratio (BER) of $2.2 \times 10^{-3}$ using non-return-to-zero on-off keying (NRZ-OOK) pseudorandom binary sequence (PRBS) $2^{10}-1$ data stream, a 375-nm laser-based communication link over the 1.15-m water channel. This proof-of-concept demonstration opens the pathway for revolutionizing the photodetection scheme in UWOC, and for non-line-of-sight (NLOS) free-space optical communication.

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1. Introduction

In recent years, visible light communication (VLC) had progressed tremendously with up to multi-Gbps data rates demonstrated [1–8]. At the same time, by utilizing the optical carrier frequency in the range of 400 to 800 THz, VLC has also been proposed as the next-generation high-throughput communication technology for complementing the saturated bandwidth in the radio frequency (RF) domain [9–11]. However, with more than 70% of the earth’s surface covered with water, underwater wireless optical communication (UWOC) remained as an attractive field of research [12–14]. This is crucial to complement various human activities in underwater environments, including oceanographic surveys, underwater vehicles communications, diver-to-diver communications, etc. Currently, acoustic communication is the dominant technique for UWOC links of up to a few tens of kilometers [12,15]. However, it suffers from low modulation frequencies due to strong attenuation of sound waves in the water, and thus limiting the data rate to only a few tens of kbps. On the other hand, RF communication in the underwater environment...
is also limited by the high conductivity of seawater that attenuates the radio waves [16,17]. To circumvent these issues, UWOC has been proposed as an alternative solution to provide a reliable and stable real-time high-data-rate transmission of up to Gbps in the underwater environment with distances of up to hundreds of meters long [18–25].

On the transmitter side, progress on the design of high-modulation-bandwidth (up to GHz) and low-cost light sources, such as light-emitting diodes (LEDs) and laser diodes (LDs) has enabled the development in these regards [26–28]. However, on the receiver side, although high-modulation-bandwidth (up to few hundreds of MHz) photodetectors and avalanche photodetectors (APD) have been commercialized, typically the active area of these detectors are limited to only few tens of millimeters-square (mm²) due to the limits in resistance and capacitance (RC) time constant [7,29,30]. Given these inherent drawbacks, fulfilling pointing, acquisition, and tracking (PAT) of the transmitted optical beam is indeed required. Challenges are more severe in the underwater environment, where light beams get strongly scattered, particularly in the ultraviolet (UV) to near-visible wavelength region [18,31]. Such inadequacy impedes the practical applications of UWOC for various applications, where PAT have to be strictly adhered. Moreover, as predicted in the framework of 6G technology, the technology will likely reconcile ocean-ground-space communication channels for greater global connectivity and coverage, which was not addressed in 5G technology [32]. As such, apart from the development on the transmitter side, large-detection-area and high-bandwidth photoreceivers are essential to relieve the PAT requirement, improve practicality, and provide a stable yet reliable underwater communication channel. We envisage that such development offers greater global connectivity for various underwater applications as well as billions of internet-of-underwater-things (IoUT) devices [33,34].

Mangeret et al. [35] and Farenc et al. [36] conducted the first experimental investigations on the use of luminescent optical fibers as optical receivers for corona discharges in high voltage systems. We note that luminescent optical fibers rely on the optical absorption of the dye molecules doped in the core of the fiber and re-emitted at another wavelength, depending on either frequency up- or down-conversion processes. The wavelength-shifted light would then propagate along the core layer and be guided to the photodiode, e.g., silicon-based photodetector, in order to convert the optical signal to the electrical signal. Similar applications based on luminescent optical fibers have also been used in neutron imaging [37], gamma-ray telescope [38], and in vivo detection of rare circulating cells [39]. For VLC, photoreceiver design based on luminescent materials for large detection area and wide field-of-view (FoV) was proposed by Manousiadis et al. in 2016 [40]. By using the sandwiched structure of the luminescent layer and microscope slide, up to 190 Mbps VLC link using the blue LED was demonstrated. In a later work, Peyronel et al. demonstrated a 2.1-Gbps communication link using orthogonal frequency division multiplexing (OFDM) with blue-to-green luminescent photoreceiver [41]. The designed detector was conceived for indoor VLC links using a blue LD. On the other hand, luminescent solar concentrators (LSC) were proposed by Dong et al. [42] to resolve the complex pointing and tracking issues in a blue-LED-based communication link. Despite these developments, the PAT requirement on the receiver side remains challenging in harsh environments such as underwater, which may limit the practical deployment of UWOC links. Moreover, our prior works [12,18] and Vavoulas et al. [43] have also highlighted the superiority and high-practicality of non-line-of-sight (NLOS) underwater communications enabled by the use of the highly scattered “UV window”, i.e., 200 to 380 nm. As such, photoreceiver designs catering for large detection area, high speed, and large angle of view are paramount for UV-based UWOC.

In this context, we demonstrate the potential of large-area photoreceiver design based on commercially available scintillating fiber over an UV-based underwater communication channel. We first present the fundamental properties of these scintillating fibers and subsequently design a large-area arrayed photoreceiver of up to 36 centimeters-square (cm²) for modulation measurement
in an underwater environment. Then, we test the performance of the large-area scintillating-fiber-based photoreceiver design at various angles of incidence. We further demonstrate the design of a practical photoreceiver design for underwater environment with large omni-directionality, high bandwidth, and high data transmission using non-return-to-zero on-off keying modulation (NRZ-OOK) scheme. Our method obviates the existing costly path of development in ultra-wide bandgap materials and devices for UV photodetection [44], while simultaneously offering a large-area and high-bandwidth detection scheme for UWOC applications.

2. Materials and methods

The used scintillating fibers are commercially available from Saint-Gobain (BCF-10). Figure 1(a) shows the arrayed packed form of scintillating fibers, forming a large photodetection area of up to 30 cm × 1.2 cm (length × width). In the scintillating fiber, the incoming light (λ1) is absorbed by the organic dye molecules doped in the core layer and Stoke-shifted into a longer wavelength (λ2), i.e., λ2 > λ1. The core structure has a refractive index (n1) of 1.60 and the cladding layer with a refractive index (n2) of 1.49. Due to the difference in the refractive index of the core (n1) and the cladding layer (n2), i.e., n1 > n2, the wavelength-shifted light would propagate along the core layer to both ends of the fiber. Figure 1(b) shows the arrayed scintillating fibers under the illumination of a 375-nm UV LD.

To verify the frequency down-conversion process of the scintillating fibers from UV to visible light, we performed the measurement of photoluminescence (PL) emission and excitation spectra. The room temperature PL emission of the scintillating fiber under pulsed excitation of 266 nm UV laser (Teem Photonics, PNU-M01210) is shown in Fig. 1(c). The emission wavelength peaks at 430 nm, with a full-width-at-half-maximum (FWHM) of approximately 54 nm. Shifting the incoming UV light beam into a longer visible wavelength, i.e. 430 nm in this case, also possesses an additional advantage of increasing the channel sensitivity when coupling to a Si-based photodiode, where the responsivity typically increases towards the longer visible wavelength region. The responsivity of Si-based photodiodes in the UV wavelength region is known to be lower than in the visible region, i.e., typically below the range of 0.1 A/W [45,46]. The use of tailored luminescent dye in the fiber core relieves the time-consuming and costly development of large-bandgap materials and devices for UV photodetection in UWOC. Figure 1(d) shows the excitation spectrum of the scintillating fibers, covering the range from 230 nm to 600 nm with 10-nm spaced intervals. The excitation spectrum was measured with the scintillating fibers illuminated using monochromatic light from an UV-enhanced Mercury-Xenon (Hg-Xe) arc lamp (Newport, 66142). The incoming light intensity was calibrated at every wavelength to 0.85 µW/cm², and light emission from the scintillating fibers was collected using a high-resolution spectrometer (Ocean Optics, HR4000). As shown in Fig. 1(d), the scintillating fiber exhibits strong UV absorption in the UVA region, i.e., 320 to 400 nm, and gradually decreases towards the UVB and UVC regions. The decreased light absorption towards the deep-UV region could also be substantially due to the reduced light transparency of the cladding layer, which is made of polymethylmethacrylate (PMMA, C₅H₈O₂), towards the UV region. The PL yield maximizes at the excitation wavelength of 370 nm, elucidating its potential for photodetection in the UV-based communication link.

Furthermore, to verify the fast conversion process of the scintillating fiber, we also measured the room temperature time-resolved photoluminescence (TRPL) decay trace. The measurements were performed with a mode-locked Ti:sapphire laser (Coherent Mira 900) having a laser power output of 1.75 W at 800 nm. A third harmonic generator (APE-SHG /THG) was used to excite the sample by an output wavelength of 266 nm (pulse width of 150 fs, pulse repetition rate of 76 MHz). A pulse-select (APE) has been used to reduce the frequency from 76 MHz to 2 MHz. Laser power on the sample was kept below 0.7 mW, and the diameter of the laser spot was 60 µm. The emission of the sample was detected by a monochromator attached to a Hamamatsu
Fig. 1. Scintillating fibers arranged in (a) large-area arrayed form and (b) while under excitation of a 375-nm UV LD. (c) Room temperature photoluminescence (PL) emission and (d) excitation spectra of the scintillating fibers used in this experiment. (e) Time-resolved photoluminescence (TRPL) decay trace and (f) Raman spectrum measured at the core layer of scintillating fiber. Inset of (e) shows the micrograph image of the cross-section of the scintillating fiber.

C6860 streak camera using a single sweep mode. The integration time was kept at 100 ms for 500 integration. As shown in Fig. 1(e), the decay curve fitted with a two-phase exponential function, reveals a fast PL decay lifetime ($\tau$) of 1.91 ns, thus confirming the feasibility of the scintillating fibers for eventual applications in the high-speed communication channels. The cross-section of the circular-shaped scintillating fiber is also shown in the inset of Fig. 1(e), where the core and cladding has a thickness of approximately 460 $\mu$m and 20 $\mu$m, respectively. Thus, the total thickness of an individual scintillating fiber used in this experiment is approximately 0.5 mm. To verify the primary structure of materials in the scintillating fibers, Raman spectrum of the core layer in the scintillating fiber was also measured using a 473-nm diode-pumped solid-state (DPSS) laser as an excitation light source. The core layer is made up of polystyrene
((C₈H₈)n)-hosted dye molecules, as shown in Fig. 1(f), where the Raman spectrum matches correspondingly well with previously reported spectra in other literature [47,48].

3. Results and discussion

Figure 2(a) shows the schematic of the experimental setup for UV-based UWOC using the large-area scintillating-fiber-based photoreceiver at the receiver end. On the transmitter side, a 375-nm laser diode (Nichia, NDU4116) is mounted on a thermoelectric cooler integrated laser mount (Thorlabs, LDM56F/M). The temperature of the LD operation is maintained at 20.5°C. The input light then passes through the water tank, filled with ASTM Type 1 Reagent Grade water. The length of the underwater channel between the transmitter and the photoreceiver is 1.15 m. On the receiver end, the tightly-packed and arrayed scintillating-fiber-based photoreceiver, as shown in Fig. 1(a), is submerged inside the water tank. The dimension of the photoreceiver is 30 cm × 1.2 cm (length × width), forming a large active detection area of up to 36 cm². Additional 20-cm long scintillating fibers were bundled and coupled to the outside of the water tank. The Stoke-shifted light from the cutting-end of arrayed scintillating fibers was then coupled through a condenser lens (Thorlabs, ACL25416U-A), a 400-nm long pass filter (Thorlabs, FELH0400), and a 100× objective lens, before being focused onto a Si-based avalanche photodetector (Thorlabs, APD430A2, f₃−dB = 400 MHz). The APD is then connected to a linear amplifier (Tektronix, PSPL5865).

Fig. 2. (a) Schematic of the experimental setup for UV-based UWOC over at 1.15-m long channel using scintillating-fiber-based photoreceiver with a large detection area of up to 30 cm × 1.2 cm (length × width). (b) Normalized small-signal frequency response of the scintillating-fiber-based photoreceiver, showing large 3-dB bandwidth at 86.13 MHz. (c) BER versus data rate over a propagation distance of 1.15 m using the designed photoreceiver.
The normalized small-signal frequency response of the large-area scintillating-fiber-based submerged photoreceiver is shown in Fig. 2(b). For bandwidth measurement, the LD is connected to the output channel of a vector network analyzer (VNA) (Agilent, E8361C). The VNA is pre-calibrated using an E-calibration module (Agilent, 85093-60010) before the experiment. The input channel of the VNA is connected to the APD through a linear amplifier. As shown in Fig. 2(b), despite the large detection area of the scintillating-fiber-based photoreceiver, it exhibits a relatively large 3-dB bandwidth of up to 86.13 MHz, which can be attributed to the fast PL decay lifetime of the polystyrene-hosted organic dye molecules in the core layer. Assuming a bi-molecular recombination mechanism [49], based on the measured 3-dB modulation bandwidth and using Eq. (1), the PL decay time ($\tau$) of the dye molecules was estimated to be in the range of 1.85 ns, which also correspond to the TRPL measurement as shown previously in Fig. 1(e).

$$\tau = \frac{1}{2\pi f_{3dB}}$$

As compared to other diode-based photoreceiver designs for communication applications, the trade-off between detection area and bandwidth remains a critical bottleneck due to the limit of RC delay in the device. This eventually impedes the subsequent deployment of various communication links, in particular for UWOC applications, where maintaining a point-to-point alignment is crucial. Differently from the design of conventional photodiodes, the scintillating-fiber-based photoreceiver design does not suffer from the issue of RC-limits, but merely depends on the PL decay time and pulse spreading in the fiber core. The 3-dB bandwidth and the large photodetection area surpasses many of the already reported UV-based photodiode designs conceived for optical communication links [7,50].

Taking advantage of the large 3-dB modulation bandwidth demonstrated by the scintillating-fiber-based photoreceiver, we have measured the data rate of the underwater communication link over the 1.15-meter long water channel using NRZ-OOK with a pseudorandom binary sequence (PRBS) $2^{10}-1$ data stream. In order to establish the measurement, as illustrated in Fig. 2(a), the LD is connected to a high-performance bit-error-ratio (BER) tester (Agilent J-BERT, N4903B) through a linear amplifier (Mini-Circuits, ZHL-6A+, 2.5 kHz to 500 MHz) for input signal generation. An analog signal generator (Agilent, E8257D, 100 kHz to 67 GHz) is used as an external clock to drive the J-BERT. The input direct current (DC) to the LD is set to 70 mA, while the alternating current (AC) amplitude is set to 400 mV. On the receiver side, the modulated signal received from the APD is connected back to the BER tester through a linear amplifier. The eye diagrams were simultaneously captured using a digital communication analyzer (Agilent, 86100C Infinium DCA-J) after passing through an attenuator (Tektronix, PSPL5510, DC to 18 GHz). Figure 2(c) shows the BER versus data rate of the 1.15-meter long underwater communication channel using the arrayed scintillating fibers as the photoreceiver. The received optical power before the APD was measured to be about 1.2 $\mu$W. A maximum data rate of 250 Mbps was recorded with a BER at $2.2 \times 10^{-3}$, which falls below the limit of forward-error-correction (FEC) of $3.8 \times 10^{-3}$. The insets of Fig. 2(c) show the clear eye diagrams of the corresponding data rates at 190 Mbps and 250 Mbps, respectively. The achieved data rate is adequate to support various underwater activities requiring high-bit rate connectivity, e.g., high-definition video streaming for oceanographic surveys, diver-to-diver communication, as well as between various underwater tactical vehicles, e.g., autonomous underwater vehicle (AUV) and submarine, without strict requirement on PAT.

We further demonstrated the potential of scintillating-fiber-based photoreceiver for a flexible, omnidirectional, and large angle-of-view detection scheme in the underwater environment. To establish the related physical parameters, we tested the received optical power and BER (at 250 Mbps as baseline) of the designed photoreceiver. As shown in Fig. 3(a), the large-area arrayed scintillating-fiber-based photoreceivers were bent and mounted across the entire width of the water tank. The transmitter based on a 375-nm UV LD is then scanned across the entire array.
of fiber-based photoreceiver, from Point 1 to Point 12, as indicated in Fig. 3(a). The angle of incidence arrived on the photoreceiver ($\theta_{inc}$) can then be estimated. Due to the relatively small width of the water tank, the maximum arrival angle of the incident light from the normal is limited to 10°.

![Figure 3](image_url)

**Fig. 3.** (a) Experimental setup for angle-dependent studies of scintillating-fiber-based photoreceiver in a 1.15-meter long water channel. (b) Received optical power, and (c) BER at 250 Mbps for different angles of incidence.

By using the same input parameter on the transmitter side, the received optical power at various angles of incidence were measured, as shown in Fig. 3(b). The received optical power was measured before entering the APD. We observed that the received optical power remained relatively stable at approximately 1.1 $\mu$W throughout the measurement range. At the same time, we have also tested the BER performance at a baseline data rate of 250 Mbps using NRZ-OOK PRBS $2^{10}-1$ data stream, as shown in Fig. 3(c). It is apparent that the BER remained lower than the FEC limit up to the maximum angle of incidence of 10°, thus elucidates the potential of scintillating fibers as the large-angle-of-view photoreceiver. The gradual increment of BER with the increase of angle of incidence could be subjected to the combined factors of the pulse-spreading effect [42], the inconsistency of dye concentration, as well as, the crosstalk between tightly packed fibers. These problems may introduce inter-symbol interference (ISI) at the demodulation end. In this context, we should stress that selective and careful considerations should be made according to these contributing factors when employing a similar design in the future. Regardless, the proof-of-concept demonstration lays a strong foundation to illustrate the unprecedented potential of scintillating-fiber-based photoreceiver for flexible and omnidirectional receiver design in underwater environments and various tactical vehicles.
Based on the physical parameters established above, we also designed a hollow structure of “parabolic-like” photoreceiver based on the scintillating fibers for large-area and omnidirectional detection in UWOC. We denote this design as “underwater optical antenna” due to the resemblance to the RF wireless antenna in terms of functionality and omni-directionality. Figures 4(a) and 4(b) shows the top-view and side-view of the “underwater optical antenna”, respectively. The center of the top section, as can be seen in Fig. 4(a), consists of double-stacked arrays of scintillating fibers, forming a detection area of 4.6 cm$^2$. The tightly-packed form of scintillating fibers is then bundled at the other end and connected to the APD. We measured the modulation performance of the “underwater optical antenna” over a 1.5-m long water channel using the same setup presented in Fig. 2(a). The normalized frequency response of the omnidirectional “underwater optical antenna” is shown in Fig. 4(c), where the 3-dB bandwidth is equal to 92.48 MHz, which is slightly higher than the bandwidth of the previous design. Moreover, as presented in Fig. 4(d), we achieved a maximum data rate of 250 Mbps with a BER of $2.5 \times 10^{-3}$ over a propagation distance of 1.5 m in the same water tank. The insets of Fig. 4(d) show the corresponding eye diagrams for bit rates of 160 Mbps and 250 Mbps. With that, we validate the performance of the large-area, omnidirectional “underwater optical antenna” before actual deployment in an underwater environment. We believe that such a design could be integrated in underwater monitoring sensors on the seafloor to ease wireless-optical-based data transmission between sensors and other vehicles during data extraction. Figure 4(e) shows the schematic illustration of the large area, omnidirectional scintillating-fiber-based photoreceiver as the sensing node for underwater wireless-optical sensor networks and simultaneously enables multidirectional wireless-optical-based communication. The significant relief on the PAT requirements may pave a way forward for UWOC, instead of relying on the size-and RC-limited photodiode designs.

| Table 1. Comparison of photoreceivers employed for optical communication link |
|--------------------------------|-----------------|----------------|-----------------|-----------------|-----------------|-----------------|
| Type of Photoreceiver          | Detection Area (cm$^2$) | Angle of View | Transmitter Wavelength | Medium of Transmission | Transmission Distance | Data Rate (Modulation Scheme) | Ref. |
| PIN                            | 0.008            | Strict alignment (0°) | 685-nm | Water | 6-m | 1.324 Gbps (128-QAM-OFDM) | [51] |
| PIN                            | $0.079 \times 10^{-3}$ | Strict alignment (0°) | 520-nm | Water | 34.5-m | 4.0 Gbps (NRZ-OOK) | [23] |
| APD                            | ~ 0.002         | Strict alignment (0°) | 520-nm | Water | 7-m | 2.3 Gbps (NRZ-OOK) | [20] |
| APD                            | ~ 0.002         | Strict alignment (0°) | 450-nm | Water | 20-m | 1.5 Gbps (NRZ-OOK) | [19] |
| Fluorescent Antibenna          | 18.75           | $\pm 60^\circ$ | 450-nm | Air | 0.5-m | 190 Mbps (OOK) | [40] |
| LSC                            | 12              | $\pm 55^\circ$ | 450-nm | Air | 0.5-m | 400 Mbps (32-QAM-OFDM) | [42] |
| Luminescent Fibers             | 126             | $\pm 25^\circ$ | 405-nm | Air | - | 2.1 Gbps (OFDM) | [41] |
| Solar Panel                    | ~ 5.0           | $\pm 14^\circ$ | 405-nm | Water | 7-m | 22.56 Mbps (64-QAM-OFDM) | [52] |
| Arrayed Scintillating Fiber    | 36.0            | $\pm 10^\circ$ | 375-nm | Water | 1.15-m | 250 Mbps (NRZ-OOK) | This work |
Fig. 4. Photograph images of: (a) top-view, and (b) side-view of “underwater optical antenna” based on scintillating fibers. (c) Normalized frequency response, and (d) BER versus data rate of the “underwater optical antenna”. (e) Schematic illustration of the large-area, omnidirectional scintillating-fiber-based photoreceivers acting as sensor nodes for UWOC applications.
Table 1 summarizes previously reported photoreceiver designs for optical communication link. Our demonstration uniquely offers a significantly large photodetection area for communication links in a harsh environment, i.e., UWOC, where fine alignment is difficult to be maintained. In this work, we address, for the first time to our knowledge, on the anomalously-large-area and omnidirectional photoreceiver design for UV-based UWOC, paving the way towards improved connectivity among several IoUT devices and applications.

4. Conclusions

In summary, we reported the design of a 36-cm$^2$ large-area UV-to-blue scintillating-fiber-based photoreceiver with a 3-dB bandwidth of 86.13 MHz suitable for UV-based UWOC applications. We achieved a data rate of 250 Mbps with a BER below the FEC limit using the NRZ-OOK modulation scheme in a 1.15-meter long water tank. As a proof of concept, we equally designed an omnidirectional photoreceiver convenient for future deployment in real sea environments. The scalable and remarkably large detection area of the scintillating-fiber-based photoreceiver simultaneously offers high modulation bandwidth, and addresses the critical challenges of size- and bandwidth-limits in traditional photodiodes used for UV-based UWOC. Thus, the proposed scheme obviates the existing costly and timely development path of ultra-wide bandgap materials for UV detection. Moreover, the scintillating-fiber-based photoreceiver offers a practical solution for large-detection-area, high-speed, and omnidirectional photodetection schemes to cater for the untapped potential of UV-based UWOC. As the photodetection scheme eases the strict PAT requirements, we envisage that such solution is practical for actual deployment in UWOC and free-space optical communication scenarios, including UV-based NLOS communication.

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