Wide-field-of-view Perovskite Quantum-dots Fibers Array for Easing Pointing, Acquisition and Tracking in Underwater Wireless Optical Communication

Chun Hong Kang[1,*], Omar Alkhazragi[1,*], Lutfan Sinatra[2], Sultan Alshaibani[1], Yue Wang[1], Kuang-Hui Li[1], Meiwei Kong[1], Marat Lutfullin[2], Osman M. Bakr[3], Tien Khee Ng[1], and Boon S. Ooi[1,†]

[1]Photonics Laboratory, Division of Computer, Electrical, and Mathematical Sciences and Engineering and [3]Division of Physical Science and Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia
[2]Quantum Solutions, 1 Venture Road, Science Park, Southampton, SO16 7NP, United Kingdom
**Authors contributed equally*
[†]Email address: boon.ooi@kaust.edu.sa

Abstract: We demonstrated, for the first time, perovskite quantum-dots optical fibers array successfully eases the pointing, acquisition and tracking requirement facing visible-laser-based underwater wireless optical communication. © 2022 The Author(s)

1. Introduction

Underwater wireless optical communication (UWOC) emerged as a paradigm-shifting communication modality in recent years to support various mobile underwater vehicles, e.g., autonomous underwater vehicles (AUVs) and submarines [1]. In particular, the use of a higher frequency range in the blue-to-green region (400 nm to 550 nm) for UWOC, allows a much higher data-carrying capability with low attenuation as compared to existing underwater communication modalities based on acoustic or radio-frequency (RF) signals that support data rates of up to kbit/s. Therefore, UWOC had been entrusted to enable many mission-critical activities, e.g., pipeline monitoring, environmental monitoring, diver-to-diver communication and deep-sea exploration.

On the transmitter end of a UWOC system, diode lasers are preferred due to their long coherence length, higher optical power, and, most importantly, higher modulation bandwidth as compared to light-emitting diodes (LEDs) [2], [3]. However on the receiver end, silicon-based photodiodes having a small detection area can impose challenging pointing, acquisition, and tracking (PAT) issues, especially when operating in a harsh environment subjected to turbulences due to changes in terms of salinity, temperature, waves or bubbles [4]. To circumvent the issue, many have envisaged a large-area, high-bandwidth and omnidirectional receiver for UWOC technology. For instance, large-area silicon-based solar cells have been employed as optical receivers in UWOC. However the achieved data rate is in the range of less than 20 Mbit/s due to the conventional resistance-capacitance (RC) limits that impose strict restriction in terms of detection size and modulation bandwidth [5], [6]. Although additional non-imaging concentrators, e.g., microlenses or compound parabolic concentrators, could be added before the receiver to improve the collection gain without sacrificing the bandwidth, these devices are subjected to étendue limits that restrict its angle-of-view and detection size [7]. In 2016, Peyronel et al. [7] proposed the use of organic-based luminescent fibers as high-speed optical receivers for visible-light communication (VLC) due to the fast conversion time of the organic dye doped within the fiber, as well as the optical gain that is no longer constrained by the étendue limits, but instead could be indefinitely large by increasing the length or number of fibers. However, as compared to its inorganic-based counterparts, the organic dyes doped in the off-the-shelf scintillating fibers have a discrete absorption band with narrow full-width at half-maximum (FWHM) that limits the free selection of excitation wavelength and are susceptible to degradation [8].

Herein, we demonstrate polymer-based scintillating fiber arrays formed by all-inorganic metal-halide perovskite quantum dots (QDs) as the color-converting dye doped in the core section for optical detection in 405-nm laser-based UWOC link. In recent years, the metal-halide perovskite quantum dots have received significant attention due to their high photoluminescence quantum yield (PLQY), fast conversion lifetime (~ns) and tunable wavelength characteristics that could play a pivotal role in enabling the next generation LEDs, solar cells or lasing devices. While there were a number of prior works that shed light on the use of perovskite QDs as a color-converting phosphor for high-speed transmitters, there were limited works on the applicability of perovskite QDs for optical receivers [9], especially as a flexible and omnidirectional receiver for underwater wireless optical communication. Our demonstration opens up a new avenue for perovskite-based QDs in enabling future internet-of-underwater-things (IoUT) applications.

2. Materials and Methods

The $CsPbBr_3$ QDs used in this work were synthesized using a modified hot-injection method reported elsewhere. Figure 1(a) shows the TEM images of the as-synthesized cubic-shaped QDs with the average edge size of around 6.7 nm. To fabricate the perovskite-based scintillating fibers, the as-synthesized QDs were dissolved in a polymerization agent, i.e., isobornyl acetate (IBOA) and photoinitiator (PI), as shown in the inset of Fig. 1(b). The photoluminescence (PL) spectrum of the sample was measured under the excitation of a 405-nm diode laser, showing a peak position in the vicinity of 515 nm with a FWHM of 20.9 nm. The absorption spectrum shows a gradual increment towards the 400 nm range. The PLQY was measured to be of more than 95%. The perovskite-based scintillating fibers were formed by injecting the QDs solution in IBOA into a preformed hollow-core PDMS fiber. Subsequently, the fibers were then cured under a high-intensity UV light source. As illustrated in the inset of Fig. 1(c), the core layer was formed by $CsPbBr_3$ QDs in IBOA polymer with the core diameter of around 950 μm and refractive index of 1.476. The cladding layer was formed by PDMS with outer cladding diameter of around 4 mm and refractive index of 1.436. Figure 1(c) shows an array of scintillating fibers forming a large-area optical receiver of about 120-mm^2 area and could be completely submerged into a water bath without any structural and material degradation. Apart from being flexible in nature, which allows reconfiguration, the angle-of-view of the perovskite-polymer scintillating fibers were also measured to be near-omnidirectional (>320°).

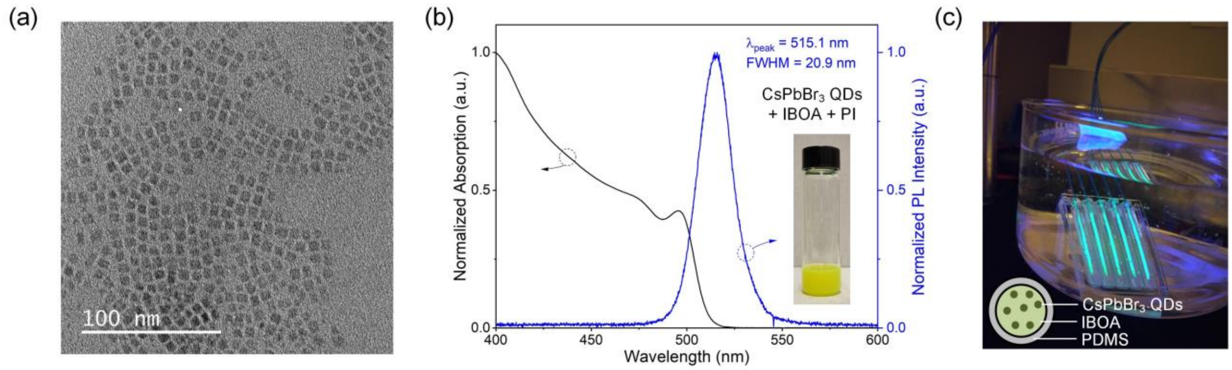

Figure 1. (a) TEM image of the $CsPbBr_3$ QDs. (b) Normalized absorbance and photoluminescence spectra of $CsPbBr_3$ QDs in IBOA and PI solution. (c) An array of perovskite-based scintillating fibers optical receivers submerged in a water bath. The inset illustrates the core and cladding layers of the as-fabricated scintillating fibers.

3. Results and Discussions

The $CsPbBr_3$ QDs-based scintillating fibers array were then tested as an optical receiver in a 1-meter-long underwater testbed filled with Type 1 Reagent Grade water, as shown in Fig. 2(a). A 405-nm diode laser (Nichia, NDV4316) was used as the data transmitter. On the receiver end, the scintillating fibers array was used as the optical receiver to collect the incoming data transmitted from the 405-nm laser and re-emit at ~515 nm before being coupled into a high-speed silicon-based avalanche photodetector (APD) (Thorlabs, APD430A2) for demodulation using large-core silica fibers. A DC-biased optical orthogonal frequency-division multiplexing (DCO-OFDM) signal is generated using an arbitrary waveform generator (AWG, Siglent, SDG6052X) with a sampling frequency of 250 MSamples/s. The output signal from the APD is amplified and then recorded using an oscilloscope (Tektronix, MDO3104) with a sampling rate of 1.25 GSamples/s.

The signal consisted of 150 OFDM symbols, the first 6 of which were used as training symbols. In other words, 4% of the signal was used for synchronization and channel estimation, which is used in post-equalization. The length of the fast Fourier transform (FFT) was set to 1024, and 194 subcarriers (spanning the frequency range from ~3 to 50 MHz) were loaded with data. The 3-MHz gap was added to avoid the baseline drift and poor slow response of the electronics in the system. A cyclic prefix was added to each OFDM symbol to minimize inter-symbol interference (ISI) and allow for single-tap equalization. The size of the cyclic prefix was set to 10.

To measure the channel capacity for each subcarrier for bit and power loading, a uniform 2-qadrature-amplitude-modulation (2-QAM) signal was used to test the system and estimate the signal-to-noise ratio (SNR) from the error vector magnitude (EVM). Based on the results, the bit and power allocation schemes shown in Figs. 2(b,c) were implemented, which gave a gross data rate of 78.8 Mbit/s. Taking into account the training symbols and the forward error correction (FEC) 7% overhead, the net data rate is around 70.2 Mbit/s. The overall bit error ratio (BER) was calculated to be 3.6×10^{-3}, which is below the 7%-overhead FEC limit (3.8×10^{-3}). The channel capacity, as well as the allocated bits are shown in Fig. 2(c) with the corresponding constellation diagrams.

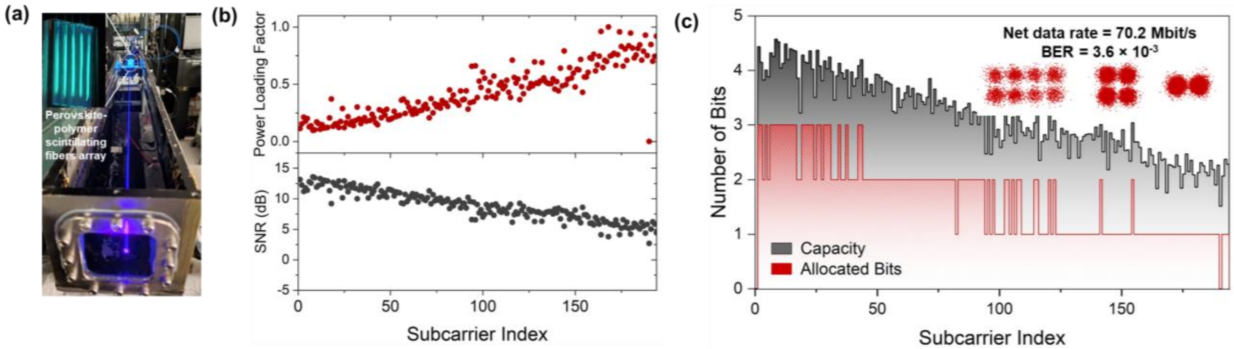

Figure 2. (a) Experimental setup of the underwater wireless optical communication link using a 405-nm laser as transmitter and the perovskite-polymer scintillating fibers as the optical receiver before coupling to a high-speed silicon-based APD. (b) The power loading factor and SNR for each subcarrier. (c) The channel capacity (in grey) and allocated bits (in red) of the established link yielding a net data rate of 70.2 Mbit/s with BER of 3.6×10^{-3}. The insets show the corresponding constellation diagrams.

4. Conclusions

In this paper, we successfully demonstrated the feasibility of perovskite QDs-based scintillating fibers as a scalable, large-area and high-bandwidth optical receiver for UWOC. Apart from opening up a new avenue of perovskite QDs for future underwater-internet systems, our demonstration could also shed light on the design of the optical receivers that relieve the strict pointing, acquisition, and tracking (PAT) requirements in UWOC technology.

Acknowledgement

The authors acknowledge funding support from the U.S. Office of Naval Research Global (ONRG) under award number N62909-19-1-2079 (KAUST reference number: RGC/3/4119-01-01) and King Abdullah University of Science and Technology (KAUST) (Grant No. BAS/1/1614-01-01, KCR/1/2081-01-01, and GEN/1/6607-01-01). T. K. N. and B. S. O. acknowledge the support from King Abdulaziz City for Science and Technology (KACST) (Grant No. KACST TIC R2-FP-008).

References

[1] H. M. Oubei, C. Shen, A. Kammoun, E. Zedini, K.-H. Park, X. Sun, G. Liu, C. H. Kang, T. K. Ng, M.-S. Alouini, and B. S. Ooi, “Light based underwater wireless communications,” *Jpn. J. Appl. Phys.*, vol. 57, no. 8S2, p. 08PA06, 2018.

[2] C. Shen, T. K. Ng, J. T. Leonard, A. Pourhashemi, H. M. Oubei, M. S. Alias, S. Nakamura, S. P. Denbaars, J. S. Speck, A. Y. Alyamani, M. M. Eldesouki, and B. S. Ooi, “High-modulation-efficiency, integrated waveguide modulator-laser diode at 448 nm,” *ACS Photonics*, vol. 3, pp. 262–268, 2016.

[3] C. Shen, J. A. Holguin-Lerma, A. A. Alatawi, P. Zou, N. Chi, T. K. Ng, and B. S. Ooi, “Group-III-Nitride Superluminescent Diodes for Solid-State Lighting and High-Speed Visible Light Communications,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 25, no. 6, p. 2000110, 2019.

[4] X. Sun, W. Cai, O. Alkhazragi, E.-N. Ooi, H. He, A. Chaaban, C. Shen, H. M. Oubei, M. Z. M. Khan, T. K. Ng, M.-S. Alouini, and B. S. Ooi, “375-nm ultraviolet-laser based non-line-of-sight underwater optical communication,” *Opt. Express*, vol. 26, no. 10, pp. 12870–12877, 2018.

[5] M. Kong, B. Sun, R. Sarwar, J. Shen, Y. Chen, F. Qu, J. Han, J. Chen, H. Qin, and J. Xu, “Underwater wireless optical communication using a lens-free solar panel receiver,” *Opt. Commun.*, vol. 426, pp. 94–98, 2018.

[6] M. Kong, J. Lin, C. H. C. H. Kang, C. Shen, Y. Guo, X. Sun, M. Sait, Y. Weng, H. Zhang, N. G. Tien Khee, B. S. B. S. Ooi, T. K. Ng, and B. S. B. S. Ooi, “Toward self-powered and reliable visible light communication using amorphous silicon thin-film solar cells,” *Opt. Express*, vol. 27, no. 24, p. 34542, 2019.

[7] T. Peyronel, K. J. Quirk, S. C. Wang, and T. G. Tiecke, “Luminescent detector for free-space optical communication,” *Optica*, vol. 3, no. 7, pp. 787–792, 2016.

[8] U. Resch-Genger, M. Grabolle, S. Cavaliere-Jaricot, R. Nitschke, and T. Nann, “Quantum dots versus organic dyes as fluorescent labels,” *Nat. Methods 2008 59*, vol. 5, no. 9, pp. 763–775, Aug. 2008.

[9] C. H. Kang, I. Dursun, G. Liu, L. Sinatra, X. Sun, M. Kong, J. Pan, P. Maity, E.-N. Ooi, T. K. Ng, O. F. Mohammed, O. M. Bakr, and B. S. Ooi, “High-speed colour-converting photodetector with all-inorganic CsPbBr3 perovskite nanocrystals for ultraviolet light communication,” *Light Sci. Appl.*, vol. 8, no. 1, p. 94, 2019.