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Underwater wireless optical communication using a lens-free solar panel receiver

Meiwei Kong [a,b], Bin Sun [a,b], Rohail Sarwar [a,b], Jiannan Shen [a,b], Yifei Chen [a,b], Fengzhong Qu [a], Jun Han [c], Jiawang Chen [a], Huawei Qin [d], Jing Xu [a,b,*]

[a] *Key Laboratory of Ocean Observation-Imaging Testbed of Zhejiang Province, Ocean College, Zhejiang University, Zheda Road 1, Zhoushan, Zhejiang, 316021, PR China*
[b] *Optical Communications Laboratory, Ocean College, Zhejiang University, Zheda Road 1, Zhoushan, Zhejiang, 316021, PR China*
[c] *School of Electrical Engineering and Telecommunications, The University of New South Wales, Australia*
[d] *The Institute of Engineering, Hangzhou Dianzi University, Hangzhou, Zhejiang, 310018, PR China*

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ABSTRACT

In this paper, we first propose that self-powered solar panels featuring large receiving area and lens-free operation have great application prospect in underwater vehicles or underwater wireless sensor networks (UWSNs) for data collection. It is envisioned to solve the problem of link alignment. The low-cost solar panel used in the experiment has a large receiving area of 5 cm^2 and a receiving angle of 20°. Over a 1-m air channel, a 16-quadrature amplitude modulation (QAM) orthogonal frequency division multiplexing (OFDM) signal at a data rate of 20.02 Mb/s is successfully transmitted within the receiving angle of 20°. Over a 7-m tap water channel, we achieve data rates of 20.02 Mb/s using 16-QAM, 18.80 Mb/s using 32-QAM and 22.56 Mb/s using 64-QAM, respectively. By adding different quantities of $Mg(OH)_2$ powders into the water, the impact of water turbidity on the solar panel-based underwater wireless optical communication (UWOC) is also investigated.

1. Introduction

The ocean, rich in huge untapped natural resources, is bearing great hopes of human beings. Developing underwater vehicles and underwater wireless sensor networks (UWSNs) is an inevitable way to promote the advancement of oceanic research and exploration. Underwater communication systems are indispensable parts of underwater equipment for underwater surveillance and data transmission. Conventional underwater acoustic communication features high reliability and stability, but it suffers limited bandwidth and large propagation delay, which is unable to satisfy certain applications requiring large data volume and high data rate. Alternatively, underwater wireless optical communication (UWOC) with high bandwidth has become a growing research trend in recent years [1–6]. Considering that underwater energy provisioning is one of the burning issues restricting the development of underwater equipment, UWOC with outstanding advantages of small size, light weight and low power consumption makes it a promising choice in underwater platforms and UWSNs. Previous research work mainly focused on stationary point-to-point UWOC with the purpose of increasing underwater transmission rate (up to several Gb/s) or distance [1–6]. Positive–intrinsic–negative (PIN) diodes [1–3] or avalanche photodiodes (APDs) [4–6] are the commonly used photodiodes (PDs). They have small active area, so convex lenses are usually employed to focus light, implying that accurate pointing is required between the transmitter and receiver. However, in practical underwater scenarios, transceiver mobility will make the link alignment very challenging and thus greatly affect the system performance. Moreover, PIN diodes/APDs usually work with biasing circuitries and trans-impedance amplifiers at the receiver side, for which external power supply is required. In fact, there are many situations where one end of the link has very limited power and even has difficulty in battery charge or replacement like the nodes of UWSNs. Such small platforms may have medium data rate requirements (1 to 100 Mb/s). Given the facts above, a solar panel-based receiver, serving the dual purpose of signal detection and energy harvesting in a UWOC system, is an interesting alternative. In recent years, solar panels used as detectors have been preliminarily studied in the field of visible light communication (VLC) [7–11]. They not only can directly convert the optical signal to an electrical signal without external power supply, but can also harvest energy from the direct current (DC) component of the modulated light to power user terminals [7]. In [9], the authors first used an organic semiconductor solar cell, which is flexible enough to be integrated on varieties of devices or substrates, as an energy-harvesting receiver for VLC. A data rate of 34.3 Mb/s

* Corresponding author at: Optical Communications Laboratory, Ocean College, Zhejiang University, Zheda Road 1, Zhoushan, Zhejiang, 316021, PR China.
E-mail address: jxu-optics@zju.edu.cn (J. Xu).

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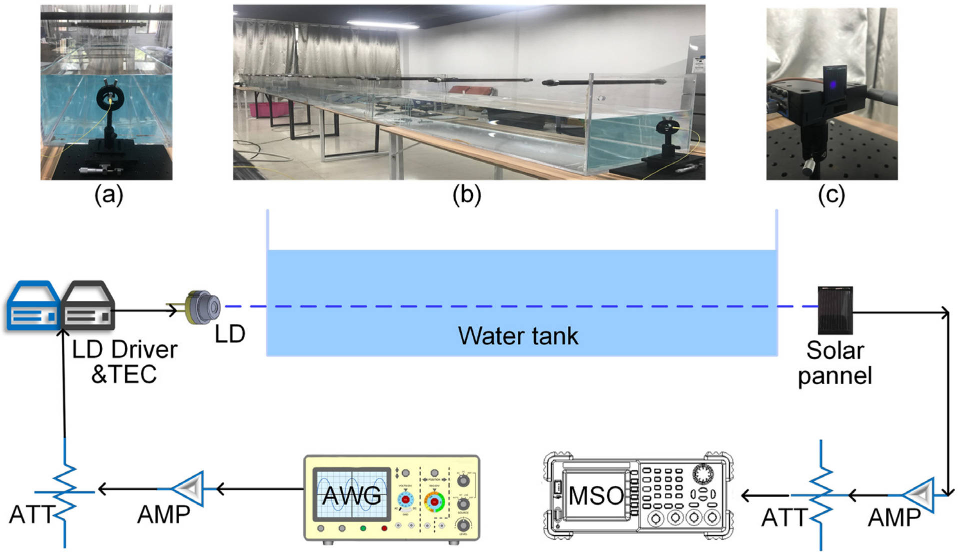

Fig. 1. Experimental setup of the proposed UWOC system using a self-powered solar panel as the detector. Insets: (a) the transmitter module, (b) the water tank, and (c) the low-cost solar panel.

was achieved using orthogonal frequency-division multiplexing (OFDM) over a 1 m air channel. The prior work renders us plentiful inspirations of future underwater equipment using solar panels, many of which could be self-powered with simultaneous wireless data transmission. However, the potential of solar panels with the advantages of large receiving area and lens-free operation, which are expected to availably solve the problem of link alignment, has not been explored.

In this paper, for the first time, we investigate the superiority of a solar panel used as a detector in a UWOC system. Compared with PIN diodes and APDs, the off-the-shelf solar panel we used has a large receiving angle of around 20° and a receiving area of around 5 cm^2, which can relax the requirement on the alignment between the transmitter and receiver. Within the receiving angle of 20°, a 20.02-Mb/s 16-quadrature amplitude modulation (QAM) OFDM signal is successfully transmitted through a 1-m air channel. Over a 7-m tap water channel, data rates of 20.02 Mb/s using 16-QAM, 18.80 Mb/s using 32-QAM and 22.56 Mb/s using 64-QAM are achieved, respectively. $Mg(OH)_2$ powders are gradually added into the water for studying the effect of water turbidity on the solar panel-based UWOC.

2. Experimental setup

Fig. 1 depicts the experimental setup of the proposed UWOC system using a self-powered solar panel as a detector. The transmitter module, the water tank and the low-cost solar panel are presented in the insets. The transmitter was a 30-mW single-mode pigtailed 405-nm LD (Thorlabs LP405-SF30) employing an LD controller and a temperature controller to set the bias current and maintain the temperature, respectively. The optimum bias current was 60 mA and the temperature was stabilized at 25 °C. 16-QAM/32-QAM/64-QAM OFDM signals generated offline and output from an arbitrary waveform generator (AWG) were first transmitted to a 25-dB amplifier (AMP) and a key-press variable electrical attenuator (ATT) to adjust the signal amplitudes. The sampling rate of the AWG was set at 125 MSamples/s in the case of transmitting 16-QAM OFDM signal and 50 MSamples/s in the case of transmitting 32-QAM/64-QAM OFDM signals. Then, the OFDM signals were superposed onto the blue-light LD via an LD and thermoelectric cooler (TEC) mount. The directly modulated light was detected by a cheap off-the-shelf silicon-based solar panel (30 mm long, 25 mm wide), after transmitting through a water tank (7 m long, 0.4 m wide, and 0.4 m high). The water tank was filled with 581.96-L fresh tap water. In the experiment, by mixing scattering agent $Mg(OH)_2$ powders with the water, some

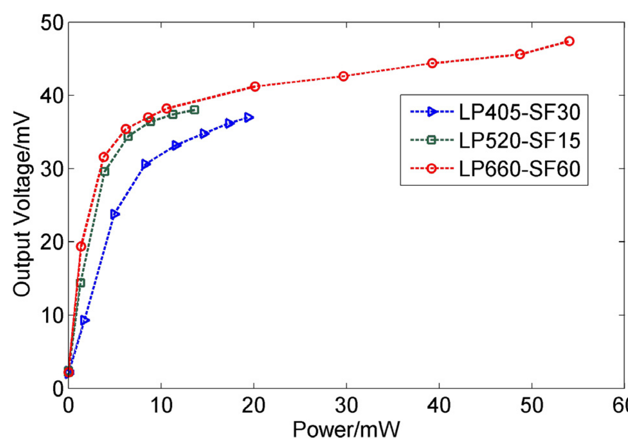

Fig. 2. Sensitivity curves of the solar panel to the 405-nm, 520-nm, and 660-nm light.

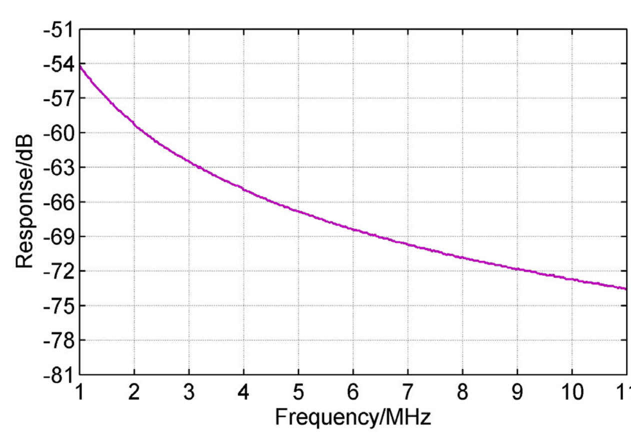

Fig. 3. Back-to-back frequency response of the system employing the 405-nm LD as the transmitter and the solar panel as the detector.

measurements were carried out. The open-circuit voltage and short-circuit current of the solar panel are 1 V and 100 mA, respectively. After