Survey of energy-autonomous solar cell receivers for satellite–air–ground–ocean optical wireless communication

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Abstract

With the advent of the Internet of Things, energy- and bandwidth-related issues are becoming increasingly prominent in the context of supporting the massive connectivity of various smart devices. To this end, we propose that solar cells with the dual functions of energy harvesting and signal acquisition are critical for alleviating energy-related issues and enabling optical wireless communication (OWC) across the satellite–air–ground–ocean (SAGO) boundaries. Moreover, we present the first comprehensive survey on solar cell-based OWC technology. First, the historical evolution of this technology is summarized, from its beginnings to recent advances, to provide the relative merits of a variety of solar cells for simultaneous energy harvesting and OWC in different application scenarios. Second, the performance metrics, circuit design, and architectural design for energy-autonomous solar cell receivers are provided to help understand the basic principles of this technology. Finally, with a view to its future application to SAGO communication networks, we note the challenges and future trends of research related to this technology in terms of channel characterization, light source development, photodetector development, modulation and multiplexing techniques, and network implementations.

Keywords: Solar cell, energy harvesting, optical wireless communication, 5G networks, Internet of Things

1. Introduction

1.1. Preliminaries

With technological advancements in recent decades, renewable solar power has been developed to be integrated into general domestic housing and utility power systems. The efficient transmission and sharing of power among large-scale, distributed, solar-powered devices have also been realized following breakthroughs in photovoltaic (PV) technology, Information Technology, intelligent management, and power electronics [1]. This is important for alleviating the energy crisis and environmental degradation. Moreover, a number of novel solar-powered products that rely on the PV effect of solar
cells to generate electricity have been developed. In addition to the mature development of solar water heaters, solar streetlights, solar PV power stations, and solar-powered satellites, PV solar cells have been integrated into autonomous vehicles, unmanned aerial vehicles (UAVs), wearable devices, and various consumer electronics devices. They are penetrating every corner of our lives and accelerating the green transformation of the global energy structure.

Recent advances in solar cell-based optical wireless communication (OWC) have led to promising market prospects for solar cells in fifth-generation (5G) communication networks and beyond for signal detection [2, 3]. The bandwidth and power conversion efficiency (PCE) of solar cells have been significantly improved to simultaneously meet the requirements of efficient energy harvesting and high-speed OWC. Compared with commonly used detectors, e.g., PIN diodes, avalanche photodiodes (APDs), and photomultiplier tubes (PMTs), solar cells are more energy efficient, environmentally friendly, and cost effective. This is because they can power user terminals (e.g., UAVs, autonomous vehicles, and various smart devices) by converting sunlight or laser light into electricity, and can convert optical signals into electrical signals based on the photovoltaic effect without any external driving power. With their attractive capabilities for simultaneous energy harvesting and signal detection, solar cells, which have been widely used in the solar energy infrastructure and various emerging new-energy devices, can play a vital role in future self-powered Internet-of-Things (IoT) systems.

1.2. Application prospects

1.2.1. Visible-light communication (VLC)

To satisfy the rapidly growing demand for data traffic, visible-light communication (VLC), offering ~340 THz of an available and unlicensed visible-light spectrum, has gained momentum in recent years. VLC is expected to significantly relieve the congested bandwidth of the conventional radio-frequency (RF) spectrum. Moreover, to facilitate large-scale deployments in future smart cities, currently available lighting infrastructures [e.g., white light-emitting diodes (LEDs)], with the advantages of energy efficiency, low cost, freedom from electromagnetic interference, and a strong layer of security, are typically used in simultaneous solid-state lighting (SSL) and VLC. On the receiver side, with increasing global awareness of energy-related issues, solar cells with the dual functions of energy harvesting and data acquisition may emerge as the preferred choice for photodetectors [4–8]. Fig. 1(a) shows the power spectral distribution of a warm-white LED and a cool-white LED [9]. Fig. 1(b) shows the air mass 1.5 (AM1.5) spectrum and the spectral response of four types of solar cells, i.e., monocrystalline silicon (m-Si), amorphous silicon (a-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) solar cells [10]. It is clear that the spectra of the white LED and the a-Si solar cell match well, particularly in the vicinity of 580 nm, where the a-Si exhibits the highest spectral response. LED- and solar cell-based VLC technology is still in its infancy, as most past work has focused on improving data rates and transmission distances without considering such effects of this on VLC channels as obstruction-, mobility-, and alignment-related issues [4–8]. The
data rates thus achieved are lower than the order of tens of Mb/s owing to the limited bandwidth of commercial white LEDs and crystalline silicon (Si)-based solar cells. The demonstrated transmission distances are mostly shorter than 1 m, which can be ascribed to the low power density of the LEDs and the low absorption coefficient of the crystalline Si-based solar cells used. To improve communication performance and implement more robust systems, exploiting LED arrays and solar cell arrays with complex digital signal processing technologies, such as orthogonal frequency-division multiplexing (OFDM), multiple-input multiple-output (MIMO), and equalization algorithms, is a promising solution. Moreover, the development of semiconductor technologies and PV technologies is undoubtedly the most powerful propelling force in the quest to meeting the requirements of next-generation applications.

![Power spectral distribution of LEDs and solar cells](image)

**Fig. 1.** (a) Power spectral distribution of a warm white LED and a cool white LED [9], and (b) the AM1.5 spectrum together with spectral response of four types of solar cells, i.e., monocrystalline silicon (m-Si), amorphous silicon (a-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) solar cells [10].

### 1.2.2. Underwater wireless optical communication (UWOC)

With the depletion of terrestrial resources and the development of marine technology, an increasing number of gliders, autonomous underwater vehicles (AUVs), remotely operated vehicles, and underwater sensor networks are being deployed in the ocean for marine exploration, resource exploitation, and environmental monitoring [11]. The amount of data that need to be collected or processed is increasing exponentially in the meanwhile. These problems impose a heavy burden on the energy budget in underwater environments because a large amount of energy is required to supply energy-intensive underwater equipment and signal processing units. Therefore, underwater acoustic communication, with the disadvantages of a small bandwidth, large latency, bulky antennas, and high power consumption, cannot meet the requirements of broadband applications in the long run [12]. By contrast, underwater wireless optical communication (UWOC) is an important means of realizing real-time underwater communication with a large capacity and low power consumption, and has potential for use in short-distance communication [13]. However, the problem of alignment is a key technical bottleneck restricting its development because UWOC channels are dynamic, and light beams may be easily affected by various perturbations, such as waves, bubbles, turbulence, and random scattering [14]. Solar cells with large areas of detection and lens-free operation have been proven to be effective in alleviating link alignment...
problems [15]. Moreover, flexible solar cells, e.g., organic solar cells [16] and thin-film a-Si solar cells [3], can be integrated with various underwater sensors and vehicles to implement the self-powered Internet of Underwater Things, where this has a range of implications in terms of solving the problem of energy shortages in underwater environments.

### 1.2.3. Free space optical communication (FSO)

Free space optical communication (FSO) is currently the key technology for solving the “Last Mile” problem occurring from the backbone of optical fibers to user terminals. It can significantly contribute to connectivity between cities and remote rural areas, high-rise buildings in urban areas, and buildings on both sides of highways or railways as well as banks of rivers that are difficult to bridge. Further, a significant amount of effort has been invested for the development of FSO-based inter-satellite, satellite-to-air, satellite-to-ground, and satellite-to-submarine communications, and has pioneered a new way to build a ubiquitous network interconnection of all things. A case in point is the Starlink broadband Internet developed by SpaceX to establish a global network unbounded by the limitations of ground infrastructure. The low-orbit satellite constellation is deployed based on conventional as well as FSO communication technologies. Compared with RF communication technology, laser-based FSO technology has such advantages as higher bandwidth, smaller receivers, and narrower beams to enhance security. In terms of the receiver, recent studies have shown that the off-the-shelf solar cells widely used for energy harvesting in satellites, buildings, and streetlights have significant application prospects in FSO for simultaneous signal acquisition [2], where this can help resolve energy-related issues. For example, a gallium arsenide (GaAs) solar cell with a high -3-dB bandwidth of 24.5 MHz and a high PCE of 42% under the 0.46-W/cm² irradiance of an 847-nm laser has shown promise for use in simultaneous power transfer and high-speed FSO [17]. Moreover, compared with the available FSO receivers, large-area solar cells are advantageous in reducing the requirements related to pointing, acquisition, and tracking (PAT), and can mitigate the effects of atmospheric disturbances, such as fog, rain, and snow.

### 1.2.4. Satellite–air–ground–ocean (SAGO) OWC

The continual development of solar technology in the fields of VLC, UWOC, and FSO is laying a solid foundation for realizing satellite–air–ground–ocean (SAGO) OWC in the future. As shown in Fig. 2, satellites, UAVs, and various smart devices on land and on/in the ocean can integrate solar cells for long-term self-powered SAGO OWC that will considerably accelerate the implementation of a globally connected IoT. For example, high-speed data exchange between underwater wireless sensor nodes and AUVs is carried out first through UWOC technology. Then, the AUVs exchange data directly with ships or float to the sea surface to exchange data with UAVs, which in turn exchange data with ships. In addition, to save cost and counter the influence of perturbations (e.g., waves and bubbles) induced by the air–water interface on the performance of UWOC, buoys can be deployed on the sea surface as relays to collect data from AUVs over a long time. The collected data can be transmitted to the ground base station by UAVs and satellites, which can in turn send control commands through
the link formed by satellites, UAVs, and buoys to control the AUVs to perform specific tasks.

Fig. 2. Illustration of satellite–air–ground–ocean optical wireless communication scenario.

1.3. **Motivation**

We propose that solar cells are critical for resolving power- and communication-related issues in urban areas, rural areas, deserts, and oceans while enabling OWC across SAGO boundaries in 5G networks and beyond. Because the primary function of solar cells is energy harvesting for household buildings, commercial plants, energy-efficient vehicles, and satellites, most surveys have focused solely on this domain of application [18]. To the best of our knowledge, this is the first comprehensive survey of recent advances in solar cells for simultaneous energy harvesting and OWC. The basic principles, research methodology, challenges, and trends of research for future applications are introduced in detail. They are useful for general readers who are first encountering this technology as well as experienced researchers in the field.

1.4. **Organization**

The remainder of this survey is organized as follows: Section 2 reviews the historical evolution of solar photovoltaic technologies and solar cells for simultaneous energy harvesting and OWC. Section 3 describes the performance metrics and circuit design of solar cells for simultaneous energy harvesting and OWC. The architecture of energy-autonomous solar cell receivers is provided in Section 4. Finally, Section 5 discusses the challenges and future prospects of this emerging technology in terms of channel characterization, light sources, photodetectors (PDs), modulation and multiplexing.
2. Research status

2.1. Overview of solar photovoltaic technologies

As an effective solution to solve the global energy crisis and the problem of environmental pollution, the use of solar PV technologies by using solar energy to generate electricity has been rapidly accelerating in recent years. Various types of solar cells based on novel materials are emerging to meet the ever-increasing market demand [19]. A general classification of different types of solar cells is provided in Fig. 3. Overall, the development of solar cells has rapidly evolved, from first-generation Si wafer-based solar cells (e.g., m-Si and polycrystalline Si solar cells) and second-generation thin-film solar cells (e.g., a-Si, CIGS, and CdTe solar cells) to the more recent third-generation solar cells based on novel light-absorbing materials (e.g., dye-sensitized, organic, and perovskite solar cells) [20]. In particular, first-generation solar cells based on mature crystalline Si-based technologies have achieved substantial stability, scalability, cost effectiveness, and efficiency for commercial deployment. Yoshikawa et al. [21] have shown that the PCE of crystalline Si heterojunction solar cells can be higher than 26%, and MacQueen et al. [22] identified an important path to improve the PCE of single-junction crystalline Si-based solar cells in the near future, i.e., closer to the Shockley–Queisser limit (30% at a band gap of 1.1 eV) that defines the maximum theoretical limit of solar energy conversion [23]. In the commercial market, m-Si solar cells with PCEs of over 20% are widely available, e.g., from SunPower (SPR-X22-370) and LG (LG360Q1C-A5). Polycrystalline Si solar cells have also achieved a high PCE of approximately 22.3%, as demonstrated by Benick et al. [24] in 2017. By contrast, the PCEs of the second-generation a-Si thin-film solar cells are still lagging behind those of first-generation solar cells owing to structural inhomogeneity [25] and light-induced degradation in terms of dangling bond density [26]. As shown in [27], the PCE of hydrogenated a-Si thin-film solar cells remains at approximately 12.69%. However, the light absorption coefficient of a-Si thin-film solar cells is higher than that of crystalline Si-based solar cells in the visible-light spectrum, which enables them to have a higher response to weak visible light [26]. In addition, second-generation a-Si thin-film solar cells based on thin film technologies can better penetrate the consumer electronics market owing to their use of a minimum amount of material, high flexibility, low cost, and light weight. In recent years, with the development of materials and processing technologies, second-generation solar cells using CIGS and CdTe have achieved PCEs as high as 22.9% and 21%, respectively [28]. This can be attributed to the fact that both CIGS and CdTe solar cells have higher absorption coefficients than a-Si thin-film solar cells in the region of longer wavelength of the solar spectrum, i.e., 700–900 nm [29]. However, the use of rare earth elements and the toxic nature of both types of solar cells remain significant obstacles to their commercial use. Following advancements in materials, third-generation solar cells based on novel materials, e.g., dye-sensitized, organic, and perovskite solar cells, have
been rapidly developed over the past 10 years. Although perovskite solar cells obtained by low-temperature solution processing still suffer from stability-related issues, a record-high PCE of up to 23.7% was reported by Jiang et al. [30] in 2017, moving a step closer toward mature Si-based technologies. More recently, a PCE of up to 28% was announced by Oxford PV in late 2018 [31]. These records, achieved by using perovskite-based materials, surpass many of those for crystalline Si solar cells. However, despite their ease of fabrication, the highest PCEs achieved for organic and dye-sensitized solar cells remain lower than those for perovskite-based materials, i.e., 11.2% and 11.9%, respectively [28].

In addition to single-junction-based solar cells, multi-junction solar cells based on the stacking of various group III–V materials, e.g., gallium indium phosphide (GaInP) and gallium indium arsenide (GaInAs), as a separate absorption layer, have also drawn significant interest owing to their enhanced light absorption fitting to the corresponding solar spectrum based on their bandgap energy that improves the overall PCE [32, 33]. Fig. 4(a) shows a typical triple-junction solar cell that includes GaInP, GaInAs, and germanium (Ge) subcells series interconnected by tunnel diodes [34]. Each subcell has a higher bandgap than the one below it so that the solar spectrum can be efficiently used [34]. As shown in Fig. 4(b), each subcell absorbs light from the spectral range closest to its bandgap, which helps reduce thermalization losses [34]. Many studies have attempted to use multi-junction solar cells as part of concentrating photovoltaics in an effort to approach the Shockley–Queisser limit. In 2020, the world-record PCE of ~47.1% was obtained by using a six-junction III–V solar cell operated under the direct spectrum at 143 Suns concentration [35]. High optical concentration is a major factor that contributes to high PCEs in multi-junction solar cells. The use of an optical element (e.g., a Fresnel lens) enables a remarkable boost in irradiance values on the active device that increases its power efficiency. However, the complexity of the design process and material growth as well as the high cost of fabrication significantly impede the commercial use of multi-junction solar cells.
2.2. Solar cells for simultaneous optical communication and energy harvesting

Over the years, the rapid progress in solar photovoltaic technologies has significantly promoted the large-scale production and application of solar cells. The primary function of solar cells is widely known to be energy harvesting for household buildings, commercial plants, streetlights, vehicles, and satellites. In recent years, driven by the rapid escalation of requirements of energy saving, researchers have extensively explored the application of solar cells to novel energy-efficient communication technologies. Light fidelity is a bidirectional OWC technology that uses visible light for downlink communication and infrared light for uplink communication. This wireless technology has been proven to be an attractive solution to energy-related problems. High-efficiency and energy-efficient semiconductor devices, e.g., LEDs and laser diodes (LDs), are used for data transmission and PIN or APDs for data reception [36]. To further reduce energy consumption, Kim and Won [4] at Kyungsung University proposed the idea of using solar cells for simultaneous energy harvesting and signal acquisition in VLC systems in 2013. A data rate of 3 kb/s over a transmission distance of 40 cm was achieved using a white LED and an Si solar cell with a limited bandwidth of ~10 kHz. This study paved the way for the use of commercial Si-based solar cells as photodetectors in VLC systems. Soon after, Haas’s research team at the University of Edinburgh made important contributions to promoting the application of solar cells to indoor VLC as well as FSO, as summarized below. In 2014, Wang et al. [5] at the University of Edinburgh showed that there is a strong relationship among the transmission distances, levels of irradiance over solar cells, and achievable data rates. Using a polycrystalline Si panel with a -3-dB bandwidth of 350 kHz and a white LED, 1-Mb/s on–off keying (OOK) signal transmission was implemented over a 39-cm air channel when the average irradiance on the solar panel was $3.5 \times 10^{-4}$ W/cm². Owing to the non-flat frequency response of the polycrystalline Si solar panel, spectrally efficient OFDM modulation technology with adaptive bit and power loading was used.
to maximize the achievable data rate. When the transmission distance was 24 cm and the average irradiance over the solar panel was $7.6 \times 10^{-4}$ W/cm$^2$, 7.01-Mb/s OFDM signal transmission was implemented. In 2015, Wang et al. [6] at the University of Edinburgh further theoretically studied and designed a solar panel-based OWC system for simultaneous energy harvesting and signal acquisition, where direct current (DC) and alternating current (AC) models of a solar panel, a receiver circuit, and the corresponding parameters were described in detail. The theory was also supported by an experiment in which an 11.84-Mb/s OFDM signal was successfully transmitted using a polycrystalline Si panel and a white LED when the peak-to-peak swing in the amplitude of the received optical signal was $0.7 \times 10^{-3}$ W/cm$^2$. In 2018, a data rate of up to 0.5 Gb/s for a 2-m OFDM-based laser link was achieved by Fakidis et al. at the University of Edinburgh and Fraunhofer Institute for Solar Energy Systems [17]. In this work, a single-junction GaAs solar cell with a diameter of 1 mm was used. By independently optimizing values of the resistor for communication and energy harvesting, a high -3-dB bandwidth of 24.5 MHz and a high PCE of approximately 42% under an irradiance of 0.46 W/cm$^2$ were achieved using an 847-nm vertical-cavity surface-emitting laser (VCSEL). It is worth noting that the single-junction GaAs solar cell harvested energy directly from the 847-nm VCSEL instead of relying on solar irradiance. In 2020, Fakidis et al. at the University of Edinburgh and Fraunhofer Institute for Solar Energy Systems further investigated the trade-off between energy harvesting and wireless communication for a 2-m wireless GaAs VCSEL and PV-based optical link [37]. A peak data rate of 997 Mb/s was achieved by using OFDM with adaptive bit and power loading [37]. Moreover, the GaAs PV receiver is shown to offer simultaneous energy harvesting with 39.3% efficiency under the irradiance of 0.41 W/cm$^2$ and a data rate of 743 Mb/s [37]. In [38], the authors improved the peak data rate to 1041 Mb/s under short-circuit conditions and the power efficiency to 41.7% under the irradiance of 0.3 W/cm$^2$ with simultaneous data transfer of 784 Mb/s. In 2019, Haas et al. [2] established an outdoor testbed at the University of Edinburgh. A data rate of 20 Mb/s was achieved over an 80-m, long-distance FSO channel using a 978-nm laser as light source and an off-the-shelf Si solar cell as photodetector. In the same year, four bidirectional OWC prototypes were developed and installed on the Orkney Islands of Scotland by Das et al. [39] at the University of Edinburgh. Simultaneous energy harvesting and signal detection was implemented by using Si solar panels and a 940-nm laser. Over a 30-m link distance, a data rate of 8 Mb/s was achieved and 5 W of power was harvested from sunlight [39]. As part of the UK 5G RuralFirst project led by Cisco, this work opened an avenue for the development of low-cost, self-powered, and plug-and-play FSO in rural areas.

This technology has also aroused significant interest among researchers across the rest of the world. For example, Zhang et al. [16] at the University of St Andrews, University of Edinburgh, and Fudan University unlocked the potential of third-generation organic solar cells based on poly({4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b’]dithiophene-2,6-diyl}{3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4-b]thiophenediyl)}:[6,6]-phenylC71-butyric acid methyl ester (PTB7:PC$_{71}$BM) blends in implementing the dual functions of communication and energy harvesting in 2015.
Although their reported PCE of 7% was lower than that of other commercial Si-based solar cells, the -3-dB bandwidth of 1.3 MHz was shown to support a high transmission data rate of 34.2 Mb/s over a 1-m air channel using a red laser and OFDM technology. Moreover, Zhang et al. [16] noted that organic solar cells printed on flexible foils can be easily integrated with a wide range of smart devices, which has important implications for implementing the IoT. In the same year, Malik and Zhang [7] at Institut Supérieur d’Electronique de Paris successfully received an 8-kb/s square wave over a 50-cm air channel with a limited bandwidth of 50 kHz. In 2016, Shin et al. [8] at Yonsei University proposed a self-reverse-biased solar panel receiver to improve performance in terms of communication and energy harvesting. With an increase in the reverse bias from 0 V to 30 V, the efficiency of conversion of solar energy of the m-Si solar cell increased from 8% to 26% with 250 lx, and its frequency response increased from 90 kHz to 120 kHz. This indicates that even if there is additional energy consumption when reverse bias is applied, the overall efficiency of energy harvesting increases compared with that in the case without a reverse bias. At a reverse bias of 30 V, maximum data rates of 3 Mb/s and 17.05 Mb/s were achieved using OOK and 4-quadrature amplitude modulation (QAM) discrete multi-tone (DMT) modulation, respectively, over a 10-cm air channel. In the same year, Carrascal et al. [40] at Universitat Politecnica de Catalunya and Fundacio i2CAT explored wake-up systems by employing a-Si thin-film solar cells for simultaneous energy harvesting and indoor VLC. As the power required of the wake-up system was lower than 30 µW, a 10-W LED was proposed for wireless power transfer in addition to illumination and VLC. Thus, a 14-m wake-up distance with no interference and a 3-m wake-up distance with interference from fluorescent light were attained. The maximum achievable data rate was 1.12 kb/s using OOK. In 2017, Wang et al. [41] at the National Chiao Tung University, Philips Electronics Ltd., Feng Chia University, and Industrial Technology Research Institute demonstrated that predistortion 4-pulse-amplitude-modulation (4-PAM) signals and a parallel resistance circuit can enhance the communication performance of an a-Si solar panel-based VLC. By reducing the parallel resistance from 1 kΩ to 100 Ω, the -3-dB bandwidth of the a-Si solar panel was increased from 70 kHz to 130 kHz while the magnitude of the optical-to-electrical response dropped from −18.2 dB to −32.3 dB. Thus, a parallel resistance of 160 Ω was chosen to optimize the bandwidth and the optical-to-electrical response of the solar panel. In this case, the data rate was increased from 20 kb/s to 1.25 Mb/s (approximately 60 times). Recently, Mica et al. [42] at the University of St Andrews and the University of Edinburgh optimized triple-cation perovskite solar cells for VLC by varying the thickness of the active layer. Under white LED illumination (incident power, 0.9 mW/cm²), the PCE varied in the range of 18%–21% for devices in the range of thickness of 170–640 nm. Using a red LD (660 nm) with an output power of 50 mW, the average -3-dB bandwidth of the system increased from 114 kHz to 400 kHz as the thickness of the active layer was increased from 60 nm to 965 nm. In this case, a maximum data rate of 56 Mb/s was achieved by using the OFDM scheme over a 40-cm air channel.

The achievements recorded by using solar cells in VLC and FSO provided a solid foundation for their application to the more challenging modality, i.e., UWOC. In 2018,
Kong et al. [15] at Zhejiang University, University of New South Wales, and Hangzhou Dianzi University first showed that using solar cells with large receiving areas and lens-free operation as photodetectors can significantly alleviate link alignment issues in complex UWOC channels. Over a 7-m tap water channel, 22.56 Mb/s OFDM signals were achieved. The impact of water turbidity on solar cell-based UWOC was also investigated by mixing powders of the scattering agent magnesium hydroxide (Mg(OH)₂) with water. In light of the daunting challenges involved in supporting highly available, reliable, and cost-effective heterogeneous data traffic in the era of 5G networks and beyond, Kong et al. [3] at King Abdullah University of Science and Technology (KAUST) and Zhejiang University showed in 2019 that commercially available a-Si thin-film solar cells have significant potential for realizing simultaneous weak-light signal detection and efficient-energy harvesting. The outstanding advantages of a-Si thin-film solar cells, such as good response to weak light, flexibility, low cost, and suitability for mass production, enable their integration into a wide range of underwater smart devices for implementing the Internet of Underwater Things. With its inherent capability for being able to detect weak light down to 1 µW/cm², a custom-designed a-Si thin-film solar cell-based receiver, called AquaE-lite, successfully received OFDM signals at data rates of 1 Mb/s and 908.2 kb/s over a 20-m long-distance air channel and a 2.4-m turbid outdoor pool water channel, respectively, under bright background light. Recently, simultaneous lightwave information and power transfer in an underwater environment with light sources and solar cells was implemented by Filho et al. [43] at KAUST that has been mooted as a promising technology to recharge batteries of the future Internet of Underwater Things (IoUT) devices. With a 430-nm blue laser, it took about 124 minutes to charge an 840-mW submerged module through a solar cell. A temperature sensor equipped on the submerged module was then activated to work for more than two hours in a water tank. Using the blue laser and the solar cell with a limited -3-dB bandwidth of 100 kHz, commands at a data rate of 500 kb/s were successfully transmitted through a 1.5-m underwater channel. Moreover, with a 4.8-W LED, it took about 1 hour and 30 minutes to charge a supercapacitor on an IoUT device. Once fully charged, one-minute-long real-time video streaming was successfully captured by an analog camera equipped on the IoUT device at a distance of 30 cm. All the preliminary results described above are important for the design of UWOC systems based on solar cells in the future, but considerable effort is still required to overcome the challenges posed by UWOC channels owing to complex underwater environments.

More recently, we upgraded the second version of AquaE-lite into a fully energy-autonomous solar cell receiver by using an m-Si solar panel with a high PCE for efficient energy harvesting, and an a-Si thin-film solar cell with a high light absorption coefficient for low-intensity optical signal detection [44]. On a laboratory testbed, 1.6-Mb/s and 1.2-Mb/s OFDM signals were achieved by using AquaE-lite and a white-light laser over transmission distances of 20 m and 30 m, respectively [44]. A field trial in a PV solar cell testbed located at KAUST was conducted to study the performance of AquaE-lite in terms of simultaneous energy harvesting and VLC. Under bright sunlight (illuminance: 75080.28 lx), energy autonomy was realized and the transmission of 1.2-
Mb/s OFDM signals was achieved over a transmission distance of 15 m, which indicates that AquaE-lite delivers excellent performance in terms of energy harvesting, anti-background noise, and low-intensity optical signal detection [44]. We also investigated the communication performance of AquaE-lite in a challenging underwater environment, i.e., turbid water, by the Red Sea, where KAUST is located. OFDM signals of 1.2 Mb/s were obtained over a transmission distance of 2 m, which is the first step toward using energy-autonomous solar cell receivers as self-powered IoT devices in underwater environments to resolve energy-related issues [44].

Fig. 5. (a) A canal of the Red Sea located at KAUST, (b) experimental scene, (c) the capsule of the transmitter, and (d) the capsule of the receiver.

Fig. 6. BERs of the received 1.2 Mb/s OFDM signals for different subcarriers after transmission through 1 m of harbor water. Inset: the corresponding constellation map, where different colors represent symbols sent over different periods.

To examine the performance of AquaE-lite in terms of solving link alignment problems, a field trial in a canal of the Red Sea located at KAUST was conducted, and is shown in Fig. 5(a). Fig. 5(b) shows the experimental scene. The underwater environment was challenging in terms of deployment-, alignment-, and communication-related issues. First, it was difficult to dive, and move the capsules of the transmitter and receiver under a turbulent underwater environment. Second, the
transmitter and receiver could not be properly aligned because the seafloor was covered with coral reef [see Figs. 5(c) and (d)]. Third, turbidity caused by dissolved substances and suspended particles posed a significant challenge to communication. Figs. 5(c) and (d) present the transmitter and receiver capsules where the white-light laser and the a-Si thin film solar cell were installed, respectively. The receiver circuit of AquaE-lite and other devices on the transmitter and receiver sides were placed on the shore. In the field trial, we obtained 1.2-Mb/s OFDM signals over a transmission distance of 1 m. Fig. 6 shows the bit error ratios (BERs) of the received 1.2-Mb/s OFDM signals for different subcarriers. As the turbid water significantly reduced the signal-to-noise ratio (SNR), the high-frequency region of the spectrum had higher BERs. However, the corresponding constellation map in the inset of Fig. 6 shows that the different symbols were still clearly distinguishable, leading to a mean BER of 2.434×10^{-3}, which was below the forward error correction limit of 3.8×10^{-3}. This indicates that AquaE-lite, due to its superiority in low-intensity optical signal detection and its large area of detection, ensured the success of the communication even though the water was turbid, and the transmitter and receiver were not properly aligned. In the future, automatic PAT schemes can be used to further ease link alignment-related issues.

We summarize the work on solar cells for simultaneous energy harvesting and communication in Table 1. Research on energy-efficient VLC, UWOC, and FSO based on solar cells is still not mature. It is important to explore novel materials and structures to further improve the PCE and frequency response of solar cells. Moreover, it is pivotal to investigate the performance of solar cell-based VLC, UWOC, and FSO while considering various complex channels to speed-up their application in future IoT systems.
| Year | Type of solar cell | PCE of solar cell | -3-dB bandwidth of solar cell | Light source | Average irradiance on the solar panel | Transmission distance (channel) | Data rate (modulation scheme) | Institution | Ref. |
|------|--------------------|-------------------|------------------------------|-------------|--------------------------------------|-------------------------------|-------------------------------|-------------|------|
| 2013 | Si solar cell      | ~20%              | 10 kHz                       | White LED   | 16 W/m²                              | 40 cm (air channel)           | 3 kb/s (OOK)                 | Kyungsung University | [4] |
| 2014 | Polycrystalline Si solar cell | - | 350 kHz                  | White LED   | 3.5 × 10⁻⁴ W/cm²                     | 39 cm (air channel)           | 1 Mb/s (OOK)                  | University of Edinburgh | [5] |
| 2015 | Polycrystalline Si solar cell | - | 350 kHz                  | White LED   | 7.6 × 10⁻⁴ W/cm²                     | 24 cm (air channel)           | 7.01 Mb/s (OFDM)              | University of Edinburgh | [6] |
| 2019 | Si solar cell      | -                 | -                            | 978-nm laser| -                                    | 80 m (air channel)            | 20 Mb/s (OFDM)                | University of Edinburgh   | [2] |
| 2019 | Si solar cell      | -                 | -                            | 940-nm laser| -                                    | 30 m (air channel)            | 8 Mb/s (OFDM)                 | University of Edinburgh   | [39] |
| 2018 | Single-junction GaAs solar cell | 42% | 24.5 MHz                  | 847-nm VCSEL | 0.46 W/cm²                           | 2 m (air channel)             | 0.5 Gb/s (OFDM)               | University of Edinburgh and Fraunhofer Institute for Solar Energy Systems | [17] |
| 2020 | GaAs solar cell   | 39.3%             | 850-nm VCSEL                | 0.41 W/cm²  | 850-nm VCSEL                         | 2 m (air channel)             | 997 Mb/s (OFDM)               | University of Edinburgh and Fraunhofer Institute for Solar Energy Systems | [37] |
| 2020 | GaAs solar cell   | 41.7%             | 850-nm VCSEL                | 0.3 W/cm²   | 850-nm VCSEL                         | 2 m (air channel)             | 1041 Mb/s (OFDM)              | University of Edinburgh and Fraunhofer Institute for Solar Energy Systems | [38] |
| 2015 | Organic (PTB7:PC71BM) | 7%              | 1.3 MHz                      | 658-nm laser| -                                    | 1 m (air channel)             | 34.2 Mb/s (OFDM)              | University of St Andrews, University of Edinburgh, and Fudan University | [16] |
| Year | Device Type          | Efficiency | Frequency | Light Source | Laser Wavelength | Distance (Channel) | Bandwidth (Modulation) | Institution/University                           |
|------|----------------------|------------|-----------|---------------|------------------|--------------------|------------------------|--------------------------------------------------|
| 2020 | Triple cation perovskite solar cells | 18%–21%    | 114–400 kHz | 660-nm laser   | -                | 40 cm (air channel) | 56 Mb/s (OFDM)         | University of St Andrews and University of Edinburgh [42] |
| 2015 | -                    | -          | 50 kHz    | White LED     | -                | 50 cm (air channel) | 8 kb/s (square wave)   | Institut Supérieur d'Electronique de Paris [7]      |
| 2016 | m-Si solar cell      | 26%        | 120 kHz   | White LED     | -                | 10 cm (air channel) | $\frac{3 	ext{ Mb/s (OOK)}}{17.05 	ext{ Mb/s (4-QAM DMT)}}$ | Yonsei University [8]                               |
| 2016 | a-Si solar cells     | -          | -         | White LED     | -                | 14 m (air channel)  | 1.12 kb/s (OOK)         | Universitat Politecnica de Catalunya and Fundacio i2CAT [40] |
| 2018 | a-Si solar cells     | -          | 6.75 kHz  | White LED     | -                | 15 cm (air channel)  | 1.25 Mb/s (4-PAM)      | National Chiao Tung University, Philips Electronics Ltd., Feng Chia University, and Industrial Technology Research Institute [41] |
| 2018 | Si solar cell        | -          | <1.5 MHz  | 405-nm laser  | -                | 7 m (underwater channel) | 22.56 Mb/s (OFDM)     | Zhejiang University, University of New South Wales, and Hangzhou Dianzi [15] |
| Year | Device Type                  | Efficiency | Frequency | Laser Type    | Power Density            | Distance         | Throughput      | Institution                                                                 |
|------|-----------------------------|------------|-----------|---------------|--------------------------|------------------|-----------------|--------------------------------------------------------------------------------|
| 2019 | a-Si solar cells            | 4.8%       | 290 kHz   | White-light laser | $< 2 \times 10^{-4}$ W/cm² | 20 m (air channel) | 1 Mb/s (OFDM) | King Abdullah University of Science and Technology and Zhejiang University [3] |
|      | a-Si solar cell and m-Si solar cells | -          | 348 kHz   | White-light laser | -                        | 2.4 m (underwater channel) | 900 kb/s (OFDM) | [4]                                                                                                                   |
| 2020 | a-Si solar cell and m-Si solar cells | -          | 348 kHz   | White-light laser | -                        | 20 m (air channel) | 1.6 Mb/s (OFDM) | King Abdullah University of Science and Technology and Zhejiang University [44] |
|      |                             |            |           |               |                          | 30 m (air channel) | 1.2 Mb/s (OFDM) | [44]                                                                                                                   |
|      |                             |            |           |               |                          | 15 m (air channel on outdoor testbed) | 1.2 Mb/s (OFDM) | [44]                                                                                                                   |
|      |                             |            |           |               |                          | 2 m (underwater channel at a port) | 1.2 Mb/s (OFDM) | [44]                                                                                                                   |
|      | a-Si solar cell and m-Si solar cells | -          | 348 kHz   | White-light laser | -                        | 1 m (underwater channel in a canal) | 1.2 Mb/s (OFDM) | This work                                                                 |
| 2020 |                             |            |           |               |                          | 1.5 m (underwater channel) | 500 kb/s         | King Abdullah University of Science and Technology [43]                                                                 |
|      |                             |            |           | 430-nm laser  | -                        | -                |                 | [43]                                                                                                                   |
3. Performance metrics and circuit design for simultaneous energy harvesting and OWC

3.1. Performance metrics for simultaneous energy harvesting and OWC

In the context of energy harvesting, the key performance metrics for evaluating and comparing different types of solar cells depend on the following parameters: (i) short-circuit current density; (ii) open-circuit voltage; (iii) fill factor; and (iv) the PCE.

The short-circuit current density is the photocurrent generated by the solar cell, expressed in the form of the current density under zero external field (i.e., 0 V). The flow of the photogenerated carriers to the electrode primarily depends on the built-in field of the solar cell. The short-circuit current density can be estimated as [45]:

\[ J_{sc} = qG (L_n + L_p), \]

where \( J_{sc} \) is the short-circuit current density, \( q \) is the elementary electric charge, \( G \) is the rate of carrier generation, and \( L_n \) and \( L_p \) denote the lengths of diffusion of the electrons and the holes, respectively. This means that the short-circuit current density can be affected by the rate of carrier generation, length of carrier diffusion [45], optical properties of the active region (e.g., absorption and reflection) [46–48], and the transparent conductive electrode (TCE) used in the solar cell [49]. New TCE materials, based on various two-dimensional (2D) materials with high transparency and conductivity, have been proposed [50–53].

The open-circuit voltage is the maximum voltage achievable by the solar cell at zero net current. At this stage, no photocurrent can be extracted because the external applied electric field is equal to the built-in electric field. The governing equation for open-circuit voltage is [45]:

\[ V_{oc} = \frac{n k T}{q} \ln \left( \frac{I_L}{I_0} + 1 \right), \]

where \( V_{oc} \) is the open-circuit voltage, \( n \) denotes the ideality factor, \( k \) is the Boltzmann constant, \( T \) is the temperature in Kelvin (K), \( I_L \) is the photocurrent, and \( I_0 \) is dark current. \( V_{oc} \) is primarily determined by the energy bandgap of the materials and the carrier recombination rate [45].

The fill factor is a primary parameter for determining the maximum power that the solar cell can deliver. Ideally, \( FF \) should be equal to one in case of the absence of series resistance and infinite shunt resistance in the solar cell. The following equation can be used to calculate the fill factor [54]:

\[ FF = \frac{I_{MP}V_{MP}}{J_{sc}V_{oc}}, \]
where $FF$ is the fill factor, $J_{MP}$ and $V_{MP}$ denote the short-circuit current density and the open-circuit voltage of the solar cell at the maximum power point, respectively.

The PCE is the fundamental parameter governing the performance of the solar cell, and can be obtained by using the ratio of usable output electrical power to the incoming light power. The PCE can be determined from [54]:

$$PCE = \frac{P_{out \text{ (Electrical)}}}{P_{in \text{ (Optical)}}} = FF \frac{J_{sc}V_{oc}}{P_{in}},$$

where $P_{out}$ and $P_{in}$ are the output electrical power and the input optical power of the solar cell, respectively.

Apart from the above key parameters for energy harvesting, the frequency response of the solar cell is pivotal for implementing OWC [55]. The frequency bandwidth of a solar cell can be limited by two dominant factors, the time of carrier transit and the resistance–capacitance (RC) time constant. In case of the carrier-limited bandwidth, the primary limiting factors may be the combined effects of the (i) carrier’s drift time across the depletion layer; (ii) its diffusion time outside the depletion layer; (iii) the carrier’s lifetime; and (iv) its trapping and detrapping times. Apart from the carrier-limited bandwidth, a method to avoid the limitation owing to the RC time constant should thus be considered. The relationship between the RC time constant and the -3-dB frequency response can be estimated by the following equation [42]:

$$f_{-3 \text{ dB}} \approx \frac{1}{2\pi R_{eq}C_t},$$

where $R_{eq}$ denotes the total resistance arising from the series resistance of the diode and load resistance, and $C_t$ denotes the total junction capacitance arising from the depletion layer, bonding pad, interconnection, and stray capacitance. It is important to note that $C_t$ can be affected by the area of the solar cell. A solar module with a large area may exhibit a low -3-dB frequency response, which is not suitable for it operation as a high-speed photodetector in OWC compared with other photodetector technologies, e.g., Si [56], III-nitride [12, 57–60], perovskites [61], and scintillating fibers [62, 63]. Thus, while improving the efficiency of energy conversion of a solar module, it is necessary to ensure that it has a high-frequency response to realize simultaneous efficient energy harvesting and high-speed communication.

### 3.2. Circuit design for simultaneous energy harvesting and OWC

To model the circuit of a solar cell for energy harvesting, a nonlinear relationship between the current and the voltage should be considered. Fig. 7(a) shows the equivalent circuit of a typical solar cell [64]. Using a diode, $D$, in parallel with a current source, $I_{PH}$, to model the generated photocurrent, the nonideals of the solar cell can be modeled using a shunt resistance, $R_{SH}$, in parallel with the current source, $I_{PH}$, and a resistance, $R_S$, in series with the connected load, which can be a battery. In such a model, the output current, $I$, is given by [65]:

$$I = I_L - I_D - I_{SH},$$

where $I_D$ and $I_{SH}$ are the currents through the parallel diode and the shunt resistance, respectively. $I_D$ can be expressed as [65]:
\[ I_D = I_0 \left( e^{V_{SH}/nV_T} - 1 \right), \quad (7) \]

where \( I_0 \) is the reverse saturation current, \( V_{SH} = V + IR_S \) is the voltage across the shunt resistance, \( n \) is the diode’s ideality factor, and \( V_T \) is the thermal voltage. The diode, \( D \), represents the diffusion phenomenon, and its ideality factor is usually assumed to be one. Another diode with an ideality factor of two can be added in parallel to the first to represent the effect of the recombination, which results in a more accurate model at the cost of higher complexity [65].

![Equivalent circuit of a solar cell](image1)

Fig. 7. (a) Equivalent circuit of a solar cell. (b) AC equivalent circuit of a solar cell [6].

Fig. 7(b) shows the AC equivalent circuit of a solar cell, where \( \omega \) is the angular frequency. The nonlinear diode is modeled in the small signal model as a resistor, \( r \), in parallel with a capacitor, \( C_D \), while the inductor \( L_w \) is used to model the inductance of the cables connected to the solar cells [6].

To use the solar cell for simultaneous energy harvesting and communication, two branches, shown in Fig. 8, are connected as a load across the two ends shown in Fig. 7(b) [6, 41]. In the communication branch, a capacitor, \( C \), connected in series to a load, \( R_C \), is used to block the DC signal. To reduce the AC signal in the energy harvesting branch, an inductor, \( L \), is connected to a battery, \( R_E \).

![Two additional branches](image2)

Fig. 8. Two additional branches used for simultaneous energy harvesting and communication [6].

The overall frequency response, \( H(\omega) \), can be expressed as [16]:

\[ H(\omega) = H_{SP}(\omega)H_L(\omega), \quad (8) \]

where \( H_L(\omega) = \frac{v(\omega)}{i_{PH}(\omega)} \), \( \omega \) is the angular frequency and \( H_{SP}(\omega) \) is the frequency response of the circuit shown in Fig. 7(b), which can be expressed as follows [16]:

\[ H_{SP}(\omega) = \frac{v(\omega)}{i_{PH}(\omega)} = \frac{Z_LZ_{eq}}{R_S + j\omega L + Z_L}, \quad (9) \]

where \( v(\omega) \) is the voltage across the load, \( i_{PH}(\omega) \) is the generated photocurrent, and
$Z_L$ is the load impedance connected to the solar cell, and is given by [16]:

$$Z_L = \frac{\omega^2 LC - j \omega (L + CR) R_E - R_E}{\omega^2 LC - j \omega (R_E + R_C) - 1}. \quad (10)$$

$Z_{eq}$ is the parallel combination of the elements shown in Fig. 7(b), and is expressed as [16]:

$$Z_{eq} = r / (1/j \omega C_D) / R_{SH} / (R_S + j \omega L_w + Z_L). \quad (11)$$

$H_L(\omega)$ can be expressed as [16]:

$$H_L(\omega) = \frac{v_o(\omega)}{v(\omega)} = \left( \frac{j \omega CR}{j \omega CR + 1} \right), \quad (12)$$

where $v_o(\omega)$ is the output signal voltage. While the optimization of values of the capacitor $C$ and the inductor $L$ depends on the solar panel used, an increase in their values has been reported to improve their performance in the low-frequency range [6]. However, the increase in capacitance degrades performance at high frequencies [6]. Moreover, the use of the harvested energy to apply a self-reverse bias on the solar cell has been shown to enhance its responsivity and response time [8].

4. Architectural design of solar cell-based receiver

There are four typical architectural designs in solar cell-based OWC systems for solar cell receivers to implement the dual functions of energy harvesting and signal acquisition, as shown in Fig. 9, adapted from RF-based simultaneous wireless information and power transfer [66].

Fig. 9(a) shows the time switching architecture, in which the solar cell-based receiver switches between the information decoding mode and the energy harvesting mode in different time slots [67]. It can be implemented using a simple hardware, but accurate time synchronization and information/energy scheduling are required.

The power-splitting architecture is illustrated in Fig. 9(b). The received signals are split into two streams at different power levels and simultaneously sent to two separate AC and DC circuits for information decoding and energy harvesting [68]. Compared with the time-splitting scheme, because no DC components are wasted in the information decoding process, the power-splitting scheme can increase the rate of energy harvesting at the expense of a more sophisticated circuit design. Moreover, in applications, it is necessary to optimize the power-splitting factor ($\alpha$), which affects the efficiency of energy harvesting and communication performance. For example, when $\alpha$ increases, the harvested energy increases while communication performance degrades owing to a reduced SNR.

In the separated receiver architecture, a solar cell array is divided into two groups to independently and concurrently perform information decoding and energy harvesting, as shown in Fig. 9(c). The number of solar cells in each group needs to be optimized according to the given system requirements by using dynamic programming [69]. Compared with the time switching scheme, the separated receiver scheme does not require stringent time synchronization. Moreover, it can speed-up the processes of energy harvesting and information decoding by using two groups of solar cells.
The spatial switching architecture is similar to the MIMO configuration as shown in Fig. 9(d). Multiple subchannels can convey either energy or information, which is sent to the corresponding energy harvesting circuit or the information decoding circuit [66]. Thus, the hardware implementation is more complex, and some optimization algorithms are needed for subchannel assignment and power allocation in different subchannels.

![Diagram of four architectural designs for solar cell receivers in OWC systems.](image)

**Fig. 9.** Architectural designs for solar cell receivers in OWC systems. (a) Time switching architecture; (b) power-splitting architecture; (c) separated receiver architecture; and (d) spatial switching architecture. Adapted from RF-based simultaneous wireless information and power transfer [66].

### 5. Challenges

#### 5.1. Solar cell-based VLC and FSO channels

One of the greatest challenges faced by solar cell-based VLC and FSO is the signal distortion caused by atmospheric channels that results in signal absorption, scattering, and fluctuation [70–75]. Atmospheric channels consist of gases, aerosols, and tiny particles suspended in the air, the concentration of which varies with altitude. Fog, snow, rain, smog, or other forms of precipitation may also be present in the atmosphere depending on the region. When light beams carrying signals pass through atmospheric channels, they may be affected by absorption, scattering, and turbulence that degrade
communication performance to varying degrees. Specifically, some of the radiation is absorbed by the molecular constituents and the energy is converted into heat, while some of the radiation undergoes scattering (e.g., Rayleigh scattering and Mie scattering) with no loss of energy. Turbulence is a temperature inhomogeneity due to the heating of the Earth’s surface by the Sun’s radiation striking it. This temperature irregularity in the atmosphere causes changes in the index of refraction of the atmosphere [76]. The interaction between light beams and turbulent media results in random variations in the amplitude and phase of signals traveling through the atmosphere. The refractive index structure parameter $C_n^2$ determines the strength of the turbulence. Among the most commonly used models is the Hufnagel–Valley model [77], which is given by:

$$C_n^2 = 0.00594 \left( \frac{\nu}{10} \right)^2 (10^{-7} h)^{10} \exp \left( - \frac{h}{1000} \right) + 2.7 \times 10^{-16} \exp \left( - \frac{h}{1500} \right) + A_0 \exp \left( - \frac{h}{100} \right),$$

where $h$ is the altitude, in m, $\nu$ is wind speed at a high altitude, in m/s, and $A_0$ is the strength of the turbulence at the ground level, $1.7 \times 10^{-14} \text{ m}^{-2/3}$.

### 5.2. Solar cell-based UWOC channels

In addition to water molecules, seawater contains a large amount of salts, phytoplankton, suspended particulate matter, and colored dissolved organic matter that cause the absorption and scattering of light [78]. The extinction coefficient $c(\lambda)$ is typically used to describe the total effect of absorption and scattering on the energy loss of light, defined by [78]:

$$c(\lambda) = a(\lambda) + b(\lambda),$$

where $\lambda$ is the wavelength of light, $a(\lambda)$ is the absorption coefficient representing the absorption of light by pure seawater, phytoplankton, detritus, and colored dissolved organic materials, and $b(\lambda)$ is the scattering coefficient that refers to changes in the direction of propagation of light due to the effects of pure seawater, phytoplankton, and detritus [78]. The dominant factor impacting absorption is the wavelength of light while the dominant factor influencing scattering is the density of the particulate matter. The values of $a(\lambda)$, $b(\lambda)$, and $c(\lambda)$ are related to the type of seawater. Thus, different types of seawater, e.g., pure seawater, clean seawater, coastal seawater, and turbid seawater, have different effects on the absorption and scattering of light, which result in different degrees of beam diffusion, light loss, and multi-path effects in the underwater transmission of light signals. Signals arriving through different paths have different transmission delays, and the received signals, superimposed with channel noise, may be seriously deteriorated.

Moreover, such dynamic factors as waves, bubbles, and turbulence (see Fig. 10) as well as the nonstationary state of transmitters and receivers lead to the time-varying characteristics of seawater channels and result in significant distortions of received signals, which leads to a high BER or even communication failure [79–81]. Several studies have been conducted on the influence of turbulence on UWOC based on PIN diodes or APDs [80, 81]. In general, turbulence is regarded as an energetic, rotational, and eddying state of motion that leads to the dispersion of materials, and the transfer of momentum, heat, and solutes at a rate much higher than that of the molecular process alone [82]. Turbulence plays a fundamental role in ocean circulation because it mixes...
the densest waters at the bottom of the ocean with lighter waters above, and in this way sends organic materials on the seafloor upward to realize circulation [83]. Oceanic turbulence can be induced by fluctuations in salinity [81] and temperature [80] in the sea as well as by bubbles [79]. These factors in turn cause variations in the refractive index of the water, and ultimately introduce random temporal and spatial irradiance as well as phase fluctuations (scintillations) of the light beam. This degrades the performance of UWOC systems [12]. Since the power spectrum of oceanic turbulence was proposed in 2000 [84], increasing attention has been paid to research on the corresponding properties in UWOC. The power spectrum of oceanic turbulence has been simplified for homogeneous and isotropic water media [85]. When the thermal diffusivity and diffusion of salt are assumed to be equal, the power spectrum of homogeneous and isotropic oceanic water is given as [86]:

\[
\Phi_h(\kappa) = 0.38 \times 10^{-8} \varepsilon^{-1/3} \kappa^{-11/3} [1 + 2.35(\kappa \eta)^{2/3}] \frac{\sigma_T}{\omega_0} \left( \omega_0^2 e^{-A_T \delta} + e^{-A_S \delta} - 2 \omega_0 e^{-A_T S \delta} \right)^2, \tag{15}
\]

where \( \varepsilon \) is the rate of dissipation of kinetic energy per unit mass of fluid, \( \kappa \) is the scalar spatial frequency, in rad/m, \( \eta \) is the Kolmogorov microscale (inner scale), \( \sigma_T \) is the rate of dissipation of the mean-squared temperature, and \( \omega_0 \) defines the proportion of the contributions of temperature or salinity to the spectrum of the refractive index. For temperature- and salinity-induced optical turbulences, the values of \( \omega_0 \) are five and zero, respectively. \( A_T, A_S, A_T S \) and \( \delta \) are constants equal to 1.863 \times 10^{-2}, 1.9 \times 10^{-4}, 9.41 \times 10^{-3}, and 8.284(\kappa \eta)^{4/3} + 12.978(\kappa \eta)^2 \), respectively.

![Fig. 10. Dynamic factors, such as waves, bubbles, turbidity, and turbulence, which degrade UWOC performance.](image)

Turbulence itself can be characterized by an energy transfer from large to small scales in which the kinetic energy is dissipated [87], whereas the strength of optical turbulence in UWOC systems is commonly characterized by the scintillation index, \( \sigma_I^2 \), of the received light beam. This is defined as the variance in the normalized received intensity and expressed as [88]:

\[
\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}, \tag{16}
\]

where \( I \) is the received intensity and \( \langle \cdot \rangle \) denotes the average over time (e.g., one
minute) [88]. Large values of the scintillation index correspond to strong turbulence that results in poor performance of UWOC systems.

Free-space atmospheric turbulence models (e.g., the lognormal distribution) were previously used to investigate the statistical distribution of fluctuations in the optical signal owing to underwater optical turbulence [89]. However, some free-space atmospheric turbulence models have been shown to not be appropriate for modeling the fluctuations in irradiance in turbulent water because the spectrum of variations in the refractive index due to temperature or salinity in water is different from that due to temperature or pressure inhomogeneities in the atmosphere [89, 90]. Moreover, the presence of bubbles needs to be considered in UWOC. A simple generalized gamma distribution has shown to be an excellent fit in weak temperature-induced turbulence [80], whereas a Weibull distribution has been proposed for salinity-induced turbulence [81]. More recently, a unified statistical model has been proposed that considers temperature gradients and the presence of bubbles in both fresh and salty water channels [90].

Solar cells with large active areas can ease PAT requirements to provide a solution that avoids the degradation introduced by oceanic turbulence. To further mitigate the effect of oceanic turbulence, various methods that have been investigated for PIN photodiode- or APD-based UWOC systems are also applicable to UWOC systems based on solar cells, such as those that use a longer wavelength of green light [91], aperture averaging by expanding the transmitted light beam and the receiving aperture [79], and the MIMO scheme [92].

5.3. Light sources

As ubiquitous energy-efficient lighting infrastructures [93, 94], LEDs are commonly employed as light sources in solar cell-based VLC systems for providing simultaneous SSL and optical wireless data transmission [8]. They have many advantages, such as a long lifetime, low cost, enhanced security, high efficiency of luminance, and no RF interference. The most commonly used white LEDs for SSL are composed of blue-emitting LEDs and yellow-emitting phosphors [95]. However, owing to the long relaxation time of phosphors, long spontaneous carrier lifetimes, and significant parasitic RC effects, LEDs have intrinsic limitations on the modulation bandwidth (few to tens of MHz) [96]. Even though the bottleneck in currently used solar cell-based VLC is at the receiver end, the eventual implementation of high-speed solar cells would require faster-than-LED devices. Moreover, owing to the low-coherence and nondirectional spontaneous emission [3], commonly used LEDs struggle to support long-distance solar cell-based VLC.

Exploiting high-power LEDs or LED arrays with advanced modulation or multiplexing techniques is an optimal means of improving data rates and transmission distances. For example, high-power red-, green-, and blue-emitting (RGB) LED arrays can not only support long-distance and high-speed solar cell-based VLC by using the wavelength-division multiplexing technique [97], but can also concurrently realize power transfer from high-power RGB LEDs to solar cells. Moreover, high-power RGB LEDs can be color-tuned to match different types of solar cells to achieve a large
photocurrent at the receiver end. For instance, they can be particularly useful when single- or multi-junction solar cells based on composition-tunable group-III-nitride-[98, 99] and group-III-phosphide-based [100, 101] materials are used in such cases. Nevertheless, high-power LEDs have a smaller modulation bandwidth as determined by their relatively large area and, therefore, a larger RC delay than regular LEDs [102].

By contrast, micro-LEDs (μLEDs) offer a much larger modulation bandwidth of hundreds of MHz, and even up to a few GHz, owing to their shorter differential carrier lifetime, owing to increased current density, together with a minimal device area (i.e., reduced RC delay) [103]. In general, commercial μLED arrays with lateral dimensions of less than 100 μm × 100 μm are composed of high-density miniaturized μLED pixels, where each pixel can be independently driven [104]. In recent years, μLED arrays have been mainly used in consumer electronics, such as applications involving large-area or head-mounted displays, micro-projectors, and wearable devices. Apart from this, they have shown significant potential in high-speed VLC as light sources [103]. However, such drawbacks as low-output power and issues arising from pixel control need to be addressed to implement SSL and long-distance VLC Many researchers have recently focused on simultaneously improving optical power and modulation bandwidth by using either series or parallel μLED arrays [105–107]. These approaches increase the effective output optical power of the emitter while retaining the high-speed characteristics of a single μLED. In this direction, high optical power and high-bandwidth μLED arrays have significant prospects in the future of simultaneous power transfer and high-speed solar-cell-based OWC systems. Fig. 11(a) shows a cross-sectional schematic of two adjacent pixels and Fig. 11(b) shows the top view of 10-pixel array of gallium nitride (GaN)-based top-emitting blue μLED chips in series [105].

![Cross-sectional schematic and top-view photograph of GaN-based top-emitting blue μLED chips in series](image)

Fig. 11. (a) Cross-sectional schematic of two adjacent pixels and (b) top-view photograph of 10-pixel array of GaN-based top-emitting blue μLED chips in series. The line AA’ in (b) is the cutting line for (a) [105].

With continual breakthroughs in semiconductor technology, LDs in the visible band are maturing. Monochromatic LDs have been used in high-speed solar cell-based OWC [15]. The temporal coherence length for a typical LD (649 nm) is 91.51 μm while that for a typical LED (632 nm) is 12.31 μm [108], illustrating the differences between them
in spectrum coverage as well as the higher degree of monochromaticity of LDs. Because the dynamics of LDs are dominated by the lifetime of photons rather than by that of the carrier, their modulation bandwidth (~ GHz) is much larger than that of LEDs [109]. Moreover, coherent and high-intensity light from LDs can help achieve long-distance data transmission after being collimated with a lens, but this increases the difficulty of link alignment. In recent years, researchers have studied white-light lasers generated by mixed RGB LDs [110–112], blue-emitting LDs exciting phosphors [109, 113], and near-ultraviolet LDs pumping RGB phosphors [114]. A diffuser is usually mounted with the LDs to produce diffused white light, and with a plano-convex lens to adjust the spot size and shape of the white light beam. Thus, white-light lasers are appealing candidates for replacing high-power white LEDs to implement simultaneous long-distance lighting and high-speed VLC in the future [3]. Moreover, compared with monochromatic LDs (e.g., red, green, or blue LDs), white-light lasers with a wide emission spectrum are more suited to increase the PCE of solar cells, such as Si-based cells. Despite this advantage, owing to the monochromatic nature of the LD, the spectral coverage of typical LD-based white light may not be as efficient as that of LEDs in terms of PCE at the receiving solar cells, such as a-Si solar cells that typically have a broad absorption spectrum spanning across the region of visible wavelength.

To meet the ever-increasing requirements for bandwidth, narrow-line visible-light distributed-feedback (DFB) lasers operating under continuous-wave (CW) injection have become more and more attractive in recent years. Thus far, green (513.85 nm) [115] and sky-blue (~480 nm) [116] indium gallium nitride (InGaN)-based DFB lasers have been developed with CW injection by integrating a high-order DFB surface grating onto a commercial InGaN-based LD. The linewidth and side-mode suppression ratio (SMSR) of the green DFB laser were 31 pm and 36.9 dB, respectively [115]. The linewidth and SMSR of the sky-blue DFB laser were ~34 pm and 42.4 dB, respectively [116]. Moreover, VLC has been implemented at up to 10.5-Gb/s by using the sky-blue DFB laser with a -3-dB bandwidth of ~1.1 GHz and a -10-dB bandwidth of up to ~2.6 GHz [116], which shows that DFB lasers have significant potential for use in future high-speed VLC. Moreover, the continual development of narrow-line DFB lasers makes possible the control and refinement of wavelengths, which is beneficial for implementing dense wavelength-division multiplexing in solar cell-based OWC to improve system capacity. Nevertheless, improving the output power of DFB lasers while maintaining a relatively high SMSR is a critical task that needs to be dealt with.

VCSELs have also attracted considerable attention in high-speed data communication applications due to their advantages of a small footprint, circular beam emission, energy efficiency, stability, large modulation bandwidth, and low cost [117–124]. However, the output power of a single-mode VCSEL is generally limited to less than 10 mW. 2D VCSEL arrays offer an effective solution for increasing the output power [124, 125]. Moreover, VCSELs emitting across a range of infrared, visible, and ultraviolet wavelengths [120] have made possible simultaneous high-speed solar cell-based OWC and laser power transfer [17].

Superluminescent diodes (SLDs) operating in the amplified spontaneous emission regime possess the advantages of both LEDs and LDs, i.e., they are droop free, and
have low temporal coherence, low speckle noise, and a large modulation bandwidth [126]. Blue-, green-, and violet-light SLDs have been developed by using semipolar or c-plane GaN substrates to support Gb/s-class VLC [126–131]. White light has also been generated by using blue-light SLDs in conjunction with commercial yellow phosphors [126–128, 130] and RGB SLDs [132]. They are expected to become the most promising light sources for implementing high-quality SSL and high-speed OWC in 5G networks and beyond. Nonetheless, improving the energy efficiency of SLDs is a major challenge in future work [133].

5.4. Photodetectors (PDs)

While solar cells with large areas of detection can be used as PDs to reduce the requirements of PAT, other types of PDs continue to be developed and deployed. To achieve high-speed OWC, conventional PDs (e.g., PIN diodes and APDs) with a large bandwidth are viewed as alternatives to solar cells because the bandwidth of the latter is generally limited to the megahertz scale. For example, in the separated receiver architecture [see Fig. 9(c)], a solar cell or a solar cell array can be used to collect energy and provide sufficient power to a single-cell PD or a PD array for high-speed OWC. Conventional Si-based PDs (e.g., PIN diodes and APDs), with the advantages of low cost and large bandwidth (up to GHz), are widely used in VLC systems [57]. However, the broad-wavelength responsivity of Si-based PDs cannot guarantee large wavelength selectiveness, and they may undergo saturation under strong sunlight that can degrade their SNR in contrast to that of solar panels [134]. Similarly, even though single-photon avalanche diodes [135] and multi-pixel photon counters [136] with high photoelectric sensitivity are considered promising for long-distance VLC or UWOC, a limited modulation bandwidth and vulnerability to background optical noise are bottlenecks. On the contrary, c-plane [57] or semipolar [58, 137] group-III-nitride-based micro-PDs (µPDs) can be tailored for visible-wavelength-selective response, which is useful for improving the received optical power and SNR by eliminating ambient noise from unwanted light sources. A record data rate of 7.4 Gb/s was recently achieved by using a semipolar InGaN/GaN multiple-quantum-well µPD, which has shown promise in supporting future multi-Gb/s VLC [137]. However, as the active area of the large-bandwidth µPD is typically limited to the range of a few hundred micrometers, link alignment-related issues are the key constraints to high-speed OWC in the future. Using wafer-scalable µPD arrays formed by individual µPDs constituting the much-needed large areas of detection is another promising alternative, even though such drawbacks as a large amount of noise, complex electronic and control circuits, and complex decoding schemes still need to be overcome. For instance, GaN-based µLED arrays have been shown to be self-powered and high-speed µPDs [138]. Compared with commercial GaAs or Si-based PDs that have broad-wavelength responsivity, the use of group-III-nitride material devices at the receiver end yields such advantages as tunable wavelength selectivity, high sensitivity, and low dark current [138], which offers a new avenue for future energy-autonomous IoT devices.

Ultraviolet (UV) light-based diffuse-line-of-sight [14] or non-line-of-sight [139] communication is expected to be another way to mitigate link alignment issues owing
to the high scattering coefficients of UV light by abundant molecules and aerosols. Moreover, UV-based communication has a higher SNR than VLC because of low background solar radiation in the UV band due to absorption by the ozone layer [14]. In a UV communication system, a PMT, with the advantages of high sensitivity and a large spectral range, is generally used as detector [139]. However, it has a bulky form factor, high power consumption (>500 V), and high operating cost [61]. A high-speed color-converting photodetection methodology was recently proposed that uses a low-cost Si-based PD and composition-tunable perovskite-based phosphor [61]. To ease PAT requirements in the presence of underwater turbulence and underwater mobility, a large light-capturing architecture over a large area based on wavelength-converting scintillating fibers was used to couple light to an Si-based PD [63]. This detection scheme was used in conjunction with UV transmitter modality to enhance diffuse line-of-sight communication.

5.5. Modulation and multiplexing techniques

Past work on solar cell-based OWC has mainly employed the OOK [8], PAM [41], OFDM [3], and multiple-input and single-output (MISO) techniques [140]. Their advantages and disadvantages in solar cell-based OWC systems are summarized in Table 2. OOK modulation is the simplest binary modulation scheme that is easy to implement with low-cost off-the-shelf hardware. However, it has a low spectral efficiency of 1 b/s/Hz. Thus, in light of the limited bandwidth of most commercial solar cells (less than tens of MHz), OOK is not suitable for high-speed solar cell-based OWC. Multi-level PAM, with high spectral efficiency and low computational complexity, can improve the data rate of solar cell-based OWC systems [41]. However, compared with OOK, PAM complicates the transmitter system, such as by requiring higher precision for the sampling clock, a pre-compensation algorithm, and a transmitter source (e.g., LEDs) with high linearity [13].

The OFDM technique has high spectral efficiency because the signal bandwidth is effectively used by employing orthogonal and overlapping subcarriers. Each subcarrier can adopt a high-order modulation format (e.g., M-ary quadrature amplitude modulation or M-ary quadrature phase-shift keying); therefore, OFDM can significantly improve spectral efficiency and transmission rate. In recent years, continual breakthroughs have been made in the use of OFDM for high-speed solar cell-based OWC [2, 3, 5, 6, 15–17]. For applications, because high-speed data signals are converted into parallel low-speed data signals and transmitted using orthogonal subcarriers, the degradation in system performance caused by frequency-selective fading can be mitigated by means of an adaptive bit and a power loading algorithm. Moreover, inter-symbol interference (ISI) attributed to the multi-path effect can be eliminated by adding cyclic prefixes (CPs). However, compared with OOK and PAM, the hardware implementation of OFDM is complex and costly. In addition, as OFDM signals are the sum of signals carried by multiple subcarriers, if the phases of the multiple subcarriers are the same or similar, the superimposed signals generate a large instantaneous power that leads to a high peak-to-average power ratio (PAPR). Consequently, power amplifiers with a larger dynamic range are generally required for
implementing OFDM; otherwise, the signals are distorted and system performance deteriorates.

To further increase the data rate and enhance the robustness of solar cell-based OWC systems, single-input and multiple-output (SIMO), MISO, and MIMO techniques have been proposed as solutions [140]. Spatial diversity or multiplexing gain can be achieved by using different system designs. Spatial diversity refers to the use of multiple light sources to send the same signals, where multiple solar cells are used to receive independently fading signals. This helps enhance the robustness of the system. To implement spatial multiplexing, the data are first divided into several data streams and then transmitted by different light sources at the transmitter. On the receiver side, the signals are received by multiple solar cells and demodulated accordingly. Thus, the transmission rate can be significantly increased. In 2016, Hsu et al. [140] tested a solar cell-based indoor visible-light positioning system by employing the MISO technique, i.e., by using three LEDs and a solar cell. When the difference in height between the LEDs and the solar cell was 2 m and the data rate was 2 kb/s, more than 85% of the measurement results had positional errors smaller than 10 cm [140]. This preliminarily proved that in addition to the large area of detection of the solar cell that can help relax requirements related to link alignment, the MISO technique using multiple LEDs can improve system reliability. However, as the MIMO, MISO, and SIMO techniques require complex signal processing, it is necessary to reasonably design the system according to the given requirements by considering appropriate coding methods, such as layered space–time coding, orthogonal space–time block coding, and space–time trellis coding.

Table 2
Advantages and disadvantages of modulation/multiplexing techniques in solar cell-based OWC systems.

| Modulation/multiplexing techniques | Advantages | Disadvantages |
|-----------------------------------|------------|---------------|
| OOK                               | Simple; Easy to implement with low-cost off-the-shelf hardware | Limited data rates in OWC owing to the low spectral efficiency of 1 b/s/Hz |
|                                   | Immune to the nonlinearity of LEDs and thus able to improve the performance of OWC systems | |
| PAM                               | High spectral efficiency | Requires LEDs with good linearity |
|                                   | Low computational complexity | |
| OFDM                              | Supports high-speed OWC owing to high spectral efficiency | Complex hardware implementation; |
|                                   | Degradation in system performance caused by frequency-selective fading can be improved by adaptive bit and power loading algorithms | High cost; |
|                                   | ISI attributed to the multi-path effect can be eliminated by adding CPs | High PAPR |
| MIMO/MISO SIMO                    | Enhances the robustness of OWC systems with spatial diversity | Complex hardware implementation; |
|                                   | Supports high-speed OWC with spatial multiplexing; | High cost |
5.6. Network implementations

With remarkable advances in solar cell-based OWC technology in recent years, developing solar cell-based OWC networks is an inexorable trend. Many higher-layer networking techniques have yet to be investigated, including for the data link layer (e.g., multiple access schemes and link configurations), network layer (e.g., relaying techniques and routing protocols), transport layer (e.g., connectivity, reliability, and flow/congestion control), and application layer [141]. Moreover, as the optical beam emitted from a light source is naturally confined to a limited range, and is susceptible to blockage, the use of optical-RF [142–145] or optical-acoustic [146] hybrid networks for simultaneous lightwave information and power transfer may become feasible solutions. For example, in [142], the relay used can simultaneously detect the optical signal and harvest energy from the first-hop VLC link, and can then retransmit the signal to mobile terminals over the second-hop RF link by using the harvested energy. To maximize the harvested energy and improve communication performance, adaptive power control, adaptive modulation, automatic PAT, and beam forming are expected to be extensively investigated and applied to different network conditions [147, 148].

6. Conclusions

In the era of the IoT, the development of solar cell-based OWC technology has shown significant potential in establishing robust, low-cost, and energy-efficient communication networks for massive smart devices. With advancements in materials and PV technology, most VLC, FSO, and UWOC systems based on various novel solar cells have shown encouraging performance in terms of data rates and transmission distances. This provides a solid foundation for the establishment of future SAGO communication networks. However, the technology is still in its infancy, and considerable effort is required to respond to various challenges related to improving data rates, extending transmission distances, complex transmission channels, novel light sources, novel PDs, hardware implementation, and network implementation.

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