



Review:

A comprehensive review of optical wireless power transfer technology

Syed Agha Hassnain MOHSAN^{†‡1}, Haoze QIAN², Hussain AMJAD³

¹Optical Communication Laboratory, Ocean College, Zhejiang University, Zhoushan 316021, China

²School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China

³Satellite Communication and Networking Laboratory, Ocean College, Zhejiang University, Zhoushan 316021, China

[†]E-mail: Hassnainagha@zju.edu.cn

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Abstract: Ground-breaking optical wireless power transfer (OWPT) techniques have gained significant attention from both academia and industry in recent decades. Powering remote systems through laser diodes (LDs) to either operate devices or recharge batteries offers several benefits. Remote LDs can remove the burden of carrying extra batteries and can reduce mission time by removing battery swap-time and charging. Apart from its appealing benefits, laser power transfer (LPT) is still a challenging task due to its low transfer efficiency. In this paper, we discuss the necessity and feasibility of OWPT and discuss several projects, working principle, system design, and components. In addition, we show that OWPT is an essential element to supply power to Internet-of-Things (IoT) terminals. We also highlight the impacts of dynamic OWPT. We outline several OWPT techniques including optical beamforming, distributed laser charging (DLC), adaptive-DLC (ADLC), simultaneous lightwave information and power transfer (SLIPT), Thing-to-Thing (T2T) OWPT, and high intensity laser power beaming (HILPB). We also deal with laser selection, hazard analysis, and received photovoltaic (PV) cell selection for OWPT systems. Finally, we discuss a range of open challenges and counter measures. We believe that this review will be helpful in integrating research and eliminating technical uncertainties, thereby promoting progress and innovation in the development of OWPT technologies.

Key words: Wireless power transmission; Optical wireless power transfer; Distributed laser charging; Laser diode; Solar cell
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1 Introduction

Wireless power transfer (WPT) is a technology in which power is transferred from a source device to a target device without using a physical link (Lu X et al., 2016). In recent years, WPT has gained significant attention from researchers and has swiftly evolved from academia towards the market. WPT has become one of the hottest topics nowadays due to the rapidly growing ubiquity of mobile devices. Meanwhile, research on energy harvesting technology has

started. A growing body of research studies is dedicated to energy harvesting from radio frequency (RF) signals, including TV signals, cellular base stations, and wireless fidelity (Wi-Fi) (Lin JC, 2006; Talla et al., 2015), which enables ultra-low power battery free devices. This technology is free from charging and replacing batteries, but providing high electric power is difficult (Costanzo et al., 2014). Thus, there is a need to develop and enhance existing WPT techniques.

Due to the flexibility and convenience of WPT technology, its market value is growing rapidly, although the transfer efficiency of WPT is lower than that of wired technology. Designing a WPT system to charge an electronic device such as smartphone

[‡] Corresponding author

ORCID: Syed Agha Hassnain MOHSAN, <https://orcid.org/0000-0002-5810-4983>

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(Kim SM and Kim, 2013b; Lee W and Yoon, 2021) is not trivial, as it must satisfy several requirements:

1. It must be able to deliver more than 1 W power. The USB 2.0 standards permit <2.5 W power (Breton et al., 2011).

2. It must ensure the user's safety. Safety concerns are paramount in the case of high power wireless transmission across a room. High power acoustic and electromagnetic (EM) waves can have deleterious effects on human health (Smagowska and Pawlaczyk-Łuszczńska, 2013).

3. It must be simple and cost-effective for successful commercialization, and practical for deployment. It must meet form factor criteria and physical specifications, as users do not like complex and heavy-weight systems with additional components.

WPT offers numerous advantages over wired technologies as it is much more secure, comfortable, and convenient in daily life. Another main advantage of using WPT is that it can effectively operate in those environments where WPT through a wired medium is hard, dangerous, and even impossible, such as underwater applications (Lu M et al., 2018). Researchers have evaluated different WPT techniques and explored various applications. The currently available WPT technologies can be categorized into EM based and non-electromagnetic (non-EM) based (Costanzo et al., 2014) ones, as shown in Fig. 1. Several WPT methods have been reported including capacitive WPT (Kline et al., 2011; Mostafa et al., 2017), magnetic resonance coupling (Kurs et al., 2007), inductive coupling (Ho et al., 2011), resonant inductive WPT (Li and Mi, 2015; Machura and Li, 2019), and optical wireless power transfer (OWPT) (Jin MHC et al., 2018) for various aerial, ground, and underwater

applications. Among these different WPT techniques, the concept of OWPT (Fig. 2) has become more attractive (Sprangle et al., 2015; Fang et al., 2019; Katsuta and Miyamoto, 2019b; Shahjalal et al., 2019).

The transmission efficiency of non-radiative coupling based transfer technology is comparatively high, so it is widely used in household devices, such as smartphone charging pads. However, the transmission distance of this technology is limited to several meters. Inductive coupling is not applicable in some scenarios because of the associated short charging distance, whereas RF-aided transfer technology can transmit power over a longer distance. The transfer efficiency of RF-based technology decreases by the square of the distance (Shinohara, 2010). Some research groups have demonstrated power harvesting from sources like radio frequency identification (RFID) readers (Clark et al., 2009), TV signals (Parks et al., 2014), and Wi-Fi (Luo and Chin, 2021). These ambient power harvesting approaches are limited to ultra-low power applications. Although RF beamforming based technology was introduced to enhance the transmission distance (Yedavalli et al., 2017), the transfer distance limitation still exists. Moreover, RF transmission causes disruptive electromagnetic interference (EMI), which affects the performance of susceptible electronic devices. EMI appears as power disturbance, electrostatic discharge, and RF interference. Magnetic resonance coupling has some disadvantages including a short operational distance of up to a few meters, difficulty in tuning the resonator, and inconvenience because of the coil weight and size in portable devices. In contrast, microwave radiation can transmit power up to a few kilometers. However, it has

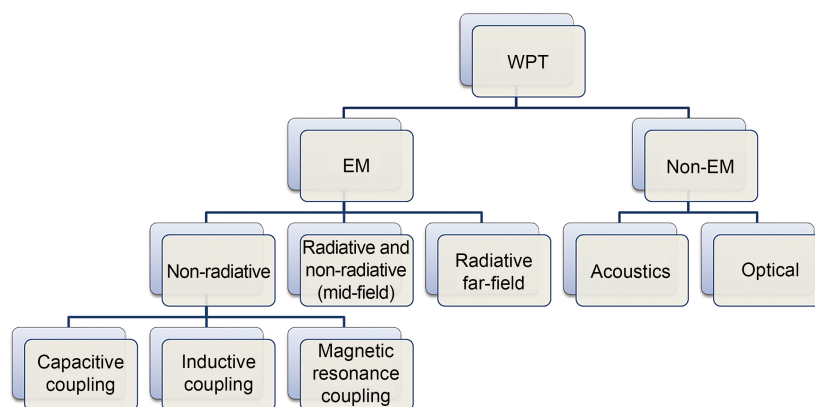


Fig. 1 An overview of wireless power transfer (WPT) technologies

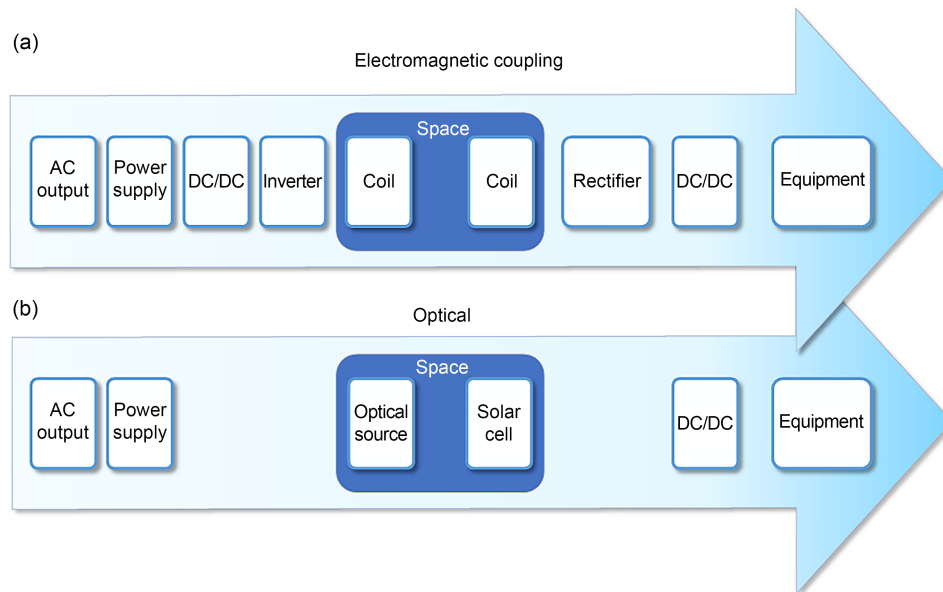


Fig. 2 Configuration of wireless power transfer (WPT) systems: (a) conventional electromagnetic (EM) induction and magnetic resonance; (b) optical wireless power transfer (OWPT) system

safety considerations when RF density exposure is high, and it is hard to collimate the intended receiver. Although energy harvesting and beamforming systems based on microwave radiation have been proposed, their availability and reliability are restricted by official regulators such as the US Federal Communications Commission (FCC), due to health and safety concerns. For these reasons, RF power transfer is not suitable for practical charging of laptops, smartphones, and other mobile devices (Zeng and Zhang, 2015; Zhang R et al., 2015a). Motivated by the above factors, we have focused on OWPT techniques in this study. We discuss a range of challenges, applications, and future prospects of this technology. This survey not only focuses on OWPT theory, but also provides guidelines for practical OWPT system design.

Previous studies have reported different OWPT techniques. Jin K and Zhou (2019) provided a comprehensive overview of laser power transfer (LPT) technology. They discussed high intensity laser power beaming (HILPB), the basic principles of laser power transmission, and suitable laser and photovoltaic (PV) cell selection. They highlighted several challenges and issues related to the implementation of LPT technology. Soltani et al. (2021) provided a tutorial for safety analysis of laser based optical wireless communication (OWC). They investigated laser beam propagation to analyze the obtained power of different laser sources.

They also presented a comprehensive framework for eye, skin, and other significant factors. Laser safety analysis with consideration of optical components like the diffuser, lens, and vertical cavity surface emitting lasers (VCSELs) was carried out. In this study, we address several OWPT techniques such as optical beamforming, HILPB, distributed laser charging (DLC), adaptive distributed laser charging (ADLC), Thing-to-Thing (T2T) OWPT, and simultaneous lightwave information and power transfer (SLIPT). Besides introducing the OWPT theory, we provide practical guidelines for OWPT system design. We outline previous studies on OWPT and the selection of components such as light emitting diodes (LEDs), suitable lasers, and PV cells. We have dedicated a complete section to LED based Internet-of-Things (IoT) assisted OWPT. Finally, we examine several challenges in OWPT and suggest necessary counter measures.

2 Optical wireless power transfer

In this section, we discuss the background knowledge of OWPT, including OWPT working principles, system design, benefits, and some projects from the literature.

OWPT can provide a promising solution to the problem of insufficient transmission distance. OWPT is

a WPT technology that considers a light source as a power transmitter. This approach can extend the transfer distance using simple system components. In OWPT, a light source such as LED (Zhou YH and Miyamoto, 2019b) or laser diode (LD) is used on the transmitter site for the conversion of electric power into optical power. A solar cell or PV cell (Takeda, 2020; Kim SM and Won, 2013) is used on the OWPT receiver site for the conversion of optical power into electric power.

Takeda (2020) demonstrated an OWPT system based on optical beamforming through white LED, but its efficiency must be improved for commercialization. In contrast, laser beams can be transmitted over long distances through collimated monochromatic light beams (Alpert and Paschotta, 2013; Kim SM and Kim, 2013a; Dasgupta et al., 2018). They allow a narrow cross-sectional beam. A laser device has several benefits over other devices, including compact layout, large coverage, and no interference with existing radios. Although microwave systems are used for solar powered satellites, OWPT systems have emerged as an alternative technology owing to their growing development. OWPT technology takes precedence over radiative RF-based technology. First, OWPT is able to transmit high power to a distant small aperture, as a laser beam can travel over a long distance (Jin and Zhou, 2019). Second, OWPT offers longer effective transmission distances than radiative RF-based technology. The laser power decreases as an exponential function, while radiative RF-based technology decreases by the square of the distance. The attenuation coefficient of OWPT is lower than that of RF. Third, OWPT also avoids EMI to neighboring electronic devices. Fourth, OWPT systems can use a PV cell as an optical receiver. This allows a mobile device to capture power from both useful optical sources and unwanted optical sources, such as sunlight. It has the capability to automatically target with accuracy. It makes use of a proper communication protocol to power any mobile device. The transfer efficiencies (Rhee and Kim, 2016) of WPT technologies with respect to distance are shown in Fig. 3.

Although the transfer efficiencies of the other technologies are higher than that of OWPT over short distances, it is envisaged that OWPT transfer efficiency would be higher over long distances. Several studies of OWPT have been published (Haydaroglu and

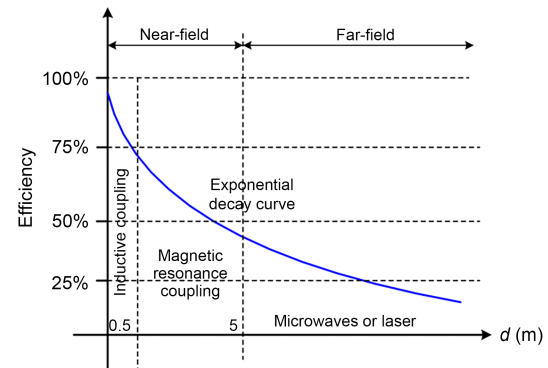


Fig. 3 Expected transfer efficiencies of wireless power transfer (WPT) technologies (Jawad et al., 2017)

Mutlu, 2015; Fakidis et al., 2016; Mostafa et al., 2017; Saha et al., 2017; Ding et al., 2020). Most have demonstrated OWPT using a laser transmitter and a solar cell receiver (Kong et al., 2020; Tang et al., 2020), while some have used LED transmitters (Zhou YH and Miyamoto, 2019a; Putra et al., 2020b). OWPT can be a promising choice for long distance WPT, but so far it has attracted little interest. Recently, some research groups (Kim SM and Park, 2020; Putra et al., 2020a) and companies such as Wi-Charge (Mantese et al., 2020) have started investigating OWPT for consumer electronics. Consumer devices such as unmanned aerial drones can be recharged through LD (Jaafar and Yanikomeroglu, 2021). The Swiss Federal Institute of Technology has developed lab-grown diamonds (Gallo, 2019), which can be used to recharge moving drones through lasers. Iyer et al. (2018) from the University of Washington, USA have introduced a smartphone charging system that uses lasers inside a room. Meanwhile, many research laboratories around the world have been focusing on OWPT for far-field regions (Katsuta and Miyamoto, 2018; Kim SM and Rhee, 2018; Xu et al., 2020). Fig. 4 illustrates different application scenarios of OWPT systems.

In the interim, the growing research interest in marine development has increased the demand for underwater robots (Gu et al., 2020; Kim J, 2020). For long-term missions using underwater robots, it would be efficient and secure to recharge batteries wirelessly (Teeneti et al., 2021). However, RF-based WPT technology is not efficient due to severe absorption in water. As visible light has relatively low absorption, visible light based OWPT can be a good choice for

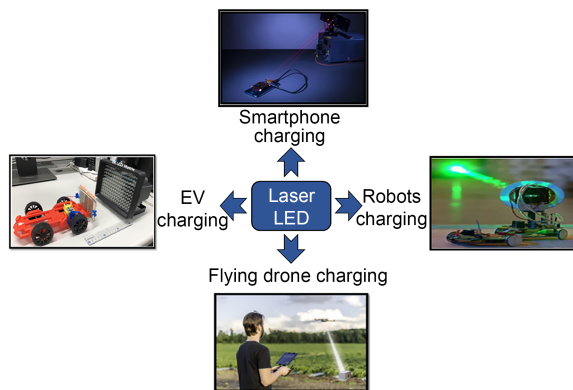


Fig. 4 OWPT applications (Summerer and Purcell, 2009; Boyle, 2018; Carron, 2018; Nguyen, 2020)

long-distance OWPT. Although many researchers have worked on OWPT, it is difficult to investigate OWPT that perfectly works in underwater environments.

Some researchers have been working on laser-based WPT systems, laser sources, high efficiency PV cells (Fakidis et al., 2018), and end-to-end power delivery systems (Iyer et al., 2018). Some previous studies focused on space-based solar power systems, aiming at energy harvesting for ground-based stations and power beaming for space exploration vehicles (Hoffert et al., 2004). In 2019, the US Naval Research Institute (NRI) successfully demonstrated a land-based power beaming system that used infrared (IR) laser (Jaffe et al., 2019). In 2020, the US Navy launched a power beaming satellite (Sanders and Kang, 2020) into space. Laser-powered devices have been proposed for unmanned aerial vehicles (UAVs) (Nugent and Kare, 2011). Also, the European Space Agency has shown interest in exploring the dark shadows of moon via laser-powered rovers (PHILIP, 2019), as shown in Fig. 5. Other devices have been proposed based on Fresnel lens solar concentrators for space applications (O'Neill et al., 2003) and laser-based ion engines for deep space missions (Wilson and Enoch, 2000).

3 OWPT projects

3.1 OWPT projects from the literature

3.1.1 Power and data transfer over light

Philips Research Laboratories invented a tech demonstrator to transmit substantial power and data over light, considering a free space link. This technique



Fig. 5 Rover testing at night (PHILIP, 2019)

can be used to power and read sensors and actuators over long distances without cables. This innovative technology has a higher optical quantum efficiency than IR. It provides higher data rates at low cost with relatively high power. It gives bidirectional communication with a data rate of more than 100 kb/s with native devices. Furthermore, it is possible to gain higher data rates if we use separate communication lasers. It can generate 3 V direct current (DC) to power sensors and processors without using converters. In this project, researchers reported 40% optical and 12% end-to-end power transfer efficiency (Mehendale, 2017). The experimental setup is presented in Fig. 6.

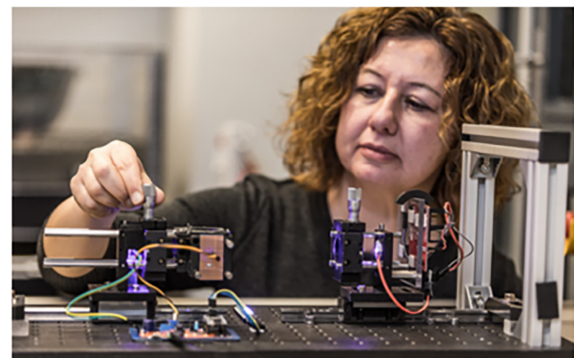


Fig. 6 Experiment for data and power transmission (Mehendale, 2017)

3.1.2 Laser-powered aircraft

To increase public awareness of the potential and viability of alternative energy sources, the National Aeronautics and Space Administration (NASA) researchers from the Marshall Space Flight Center, Dryden Flight Research Center, and the University

of Alabama, USA demonstrated a ground-breaking IR laser based aircraft flight (Gibbs, 2017), as shown in Fig. 7. The aircraft was fitted with a 1.5 kW diode at 940 nm and an IR sensitive thin film PV array. It was outfitted with PV cells that can capture propulsive power from a ground based laser system to power its tiny 6 W motor. It was a lightweight radio-controlled model airplane, designed using carbon fiber tubing and balsa wood. The aircraft body was covered by a cellophane like material, which was a ground-breaking technology for future LPT systems. Later, researchers introduced the Zephyr HALE (high altitude, long endurance) UAV, which can fly overnight. The power beaming concept was used to enhance payload capacity, day/night recharging, range, flight duration, and operational flexibility. Later, the Lockheed Martin Stalker was demonstrated, which can operate continuously for 48 h. The aircraft has the ability to fly in day or night, and can track accurately under strong wind conditions.

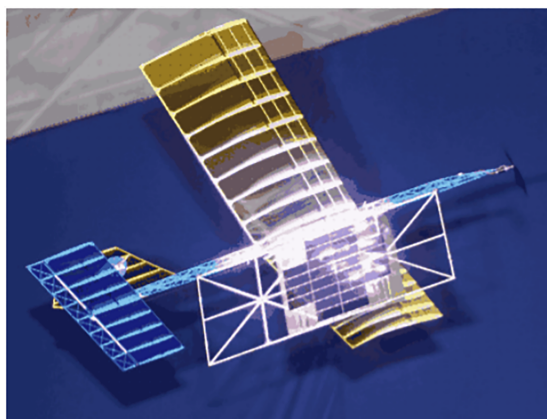


Fig. 7 Laser-powered aircraft (Gibbs, 2017)

3.1.3 Autonomous rover

OWPT is also a very helpful technology for driving autonomous vehicles. Steinsiek (2003) from EADS Astrium developed ground-to-ground WPT through LDs. Researchers demonstrated this technology using a small, completely independent rover vehicle integrated with PV cells (Fig. 8). It was considered as the first step towards powering lunar surface rovers and airships. The experiment was demonstrated using a green frequency-doubled Nd:YAG laser of only a few watts, while a micro-camera was mounted on the rover as a payload for pointing and

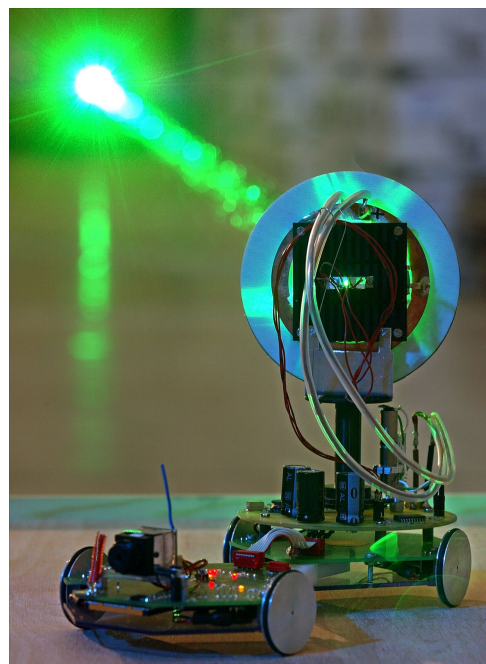


Fig. 8 EADS developed laser-powered rover (Summerer and Purcell, 2009)

position tracking purposes for distances of up to 280 m by implementing active control loops.

3.1.4 OWPT for smartphone charging

OWPT can also bring us comfort and convenience. Researchers from the University of Washington, USA proposed a secure novel method to charge smartphones with a laser, requiring minimal instrumentation to the environment. They demonstrated that a laser can be used to charge a smartphone, like a standard USB cable. They successfully delivered more than 2 W at 4.3 m for a smartphone, and at 12.2 m for a table-top form factor receiver. An invisible narrow laser beam in the IR spectrum was used for charging, while a thin power cell array was mounted on the back of smartphone. To ensure safety, they used a metal heatsink, such as aluminum strips, to dissipate excessive heat from the charging system. A retro-reflector mechanism was used as a sensor to terminate the system if a person or object appeared in the path of the guard beam. Researchers were able to turn off the laser source at a maximum speed of 44 m/s, which reduced the exposure of human tissue to the high power laser. The heat dissipation and robust safety features may enable charging of tablets, cameras, and even computers in the future. Fig. 9 shows an overview

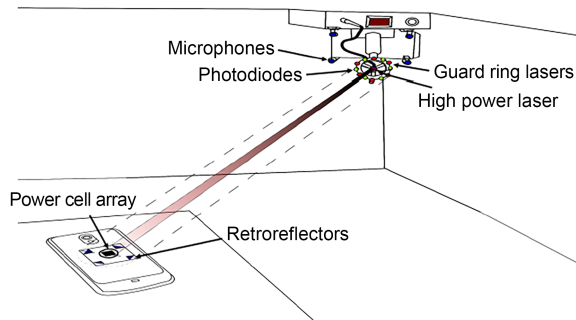


Fig. 9 Smartphone charging system (Iyer et al., 2018)

of the OWPT system developed by the University of Washington.

3.1.5 OWPT system for mobile objects

Charging has always been a more difficult task for mobile objects. OWPT can be used for charging and tracking in consumer electronics. The process of charging mobile objects is called dynamic OWPT (DOWPT). This concept has been demonstrated through various experiments based on visible and invisible light for terrestrial and space applications. To validate the concept of DOWPT with visible light, solar energy is kept in a device containing Li-ion battery, DC-AC, and DC-DC converters. This device is used to deliver power to an LED light bulb fitted to a small electric vehicle (EV). This LED light bulb of 8 W is used as a transmitter, while a small solar panel is mounted on another EV as a receiver. The proposed DOWPT system can operate at a maximum distance of 5 cm. It provides 2% efficiency at zero distance, and 1.57% at 3 cm (Nguyen, 2020). For invisible light, a light source IR LED array of 850 nm is used, considering the same small EV. The overall reported efficiency is similar to that of the visible light experiment. This idea is illustrated in Fig. 10.

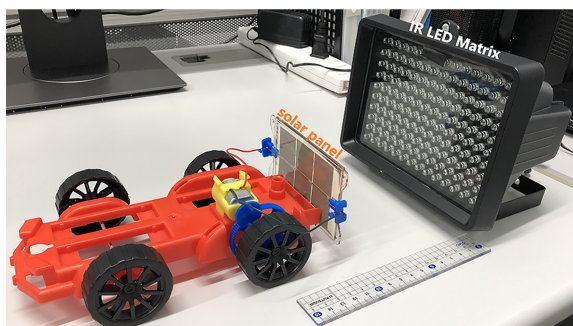


Fig. 10 DOWPT using invisible light (Nguyen, 2020)

3.2 OWPT working principle

The basic OWPT system is based on a transmitter unit (optical source) and a receiver unit (solar panel or photodiode (PD)). A high-efficiency optical source such as LD is used to convert electrical signals into a highly collimated beam, which can be transmitted over several meters with trivial losses (Kim SM and Kim, 2013b; Tang and Miyamoto, 2019). The solar cell receiver is used to convert optical signals into electric power. A DC circuit is used to operate the light source, while a solar cell gives a stable DC output. It is possible to achieve long-distance power transfer with a simple and compact system design. This system does not affect surrounding devices with EM noise.

A wireless transfer technique requires significant light irradiation to a solar cell from the optical source. Power transfer efficiency decreases and light is wasted when the solar cell receiver area is smaller than the light irradiated area. Moreover, the conversion efficiency of the solar cell decreases. Thus, high efficiency can be maintained through an accurate irradiation beam size. Another factor that degrades the performance of an OWPT system is attenuation loss by the medium. The operation can be made unstable by weather- and time-dependent power generation (Rühle, 2016). As a result, the OWPT system suffers from high losses in bad atmospheric conditions, owing to the characteristics of light, which is highly absorbed and scattered by aerosols in the atmosphere. Furthermore, laser light cannot penetrate rainfall and clouds. Some other critical concerns are pointing errors, blockages, mobility, and powering multiple devices.

To tackle these challenges, a beam control system, a stable monochromatic light source, and an efficient solar cell receiver are essential for an OWPT system (Kim SM and Won, 2013). A monochromatic light source such as LD is suitable for OWPT systems to obtain high conversion efficiency in the solar cell receiver. A DC-DC circuit can operate efficiently with a few volts of output from a solar cell (Katsuta and Miyamoto, 2017; Xu et al., 2020). Two types of solar cells are commercially available: GaAs solar cells and Si solar cells (Yamaguchi, 2003; Lee TD and Ebong, 2017; Matsuura et al., 2021). A single-chip GaAs solar cell provides 0.9–1.1 V output (Kim SM and Rhee, 2018; Matsuura et al., 2021), while a

single-chip Si solar cell provides 0.5–0.7 V output, which is insufficient to operate a DC-DC converter circuit. To increase the output voltage, a viable solution is to use multiple chips of solar cells in series. In this way, GaAs and Si solar cells can be used in OWPT systems with a series arrangement of multiple chips.

3.3 OWPT system design

An OWPT system has the advantage of delivering high intensity power over a long distance due to a small divergence angle and the small size of the laser beam. As the laser beam is small, it must be pointed accurately at the receiver. However, an additional device is required for laser beam steering. Different methods are used for beam steering and target recognition. In some studies, a four-element PD was used to detect and pinpoint the position of the target (Kawashima et al., 2007). Other researchers used a retro-directive mirror for this purpose (Wang X et al., 2016; Lim et al., 2019). Nonetheless, a perfect alignment between transceiver components is required to use these techniques. In this scenario, power delivery to a mobile target is difficult. Recently, Putra et al. (2020a, 2020b) used DOWPT for mobile objects using an IR LED marker, a web camera with OpenCV image processing software, and beam steering using a Galvano mirror. Fig. 11 illustrates the OWPT system design. Researchers have explored OWPT system components and performance in different application scenarios, including energy-hungry missions of flying drones and powering electronic devices (Kawashima et al., 2007; Parello et al., 2014), charging underwater vehicles and sensors (Jawad et al., 2017; Putra et al., 2019), charging implantable medical devices, e.g., a pacemaker (Murakawa et al., 1999; Goto et al., 2001), and to deliver power to satellite and moon rovers (Shi et al., 2016).

4 OWPT components and research contributions

In this section we introduce several studies considering OWPT system components. We also briefly compare different optical sources, such as IR LED, edge emitting laser (EEL), and VCSEL.

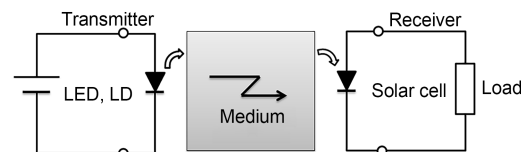


Fig. 11 Basic design of an OWPT system

In OWPT, a semiconductor laser is appropriate to generate collimated light. Although EELs can be used, VCSEL (Iga, 2008) are preferable. A VCSEL has potential advantages of light output by a two-dimensional (2D) array, and offers scalable array size. In the last two decades, several studies have reported laser-based WPT strategies for different application scenarios. A laser-based OWPT system was first introduced for solar powered satellite application (Xu et al., 2020). Steinsiek (2003) used a 532 nm solid state LD for powering a mobile rover over a distance of 30–200 m. Steinsiek (2003) investigated the feasibility of a WPT link between a transmitter and a remote receiver. Hirota et al. (2015) demonstrated an OWPT system using a 975 nm VCSEL array and common Si solar cells. They successfully achieved 33% power generation efficiency using Si solar cell. Shi et al. (2015) reported a laser-based WPT system used on airships at a transmission distance of 50–100 m. They achieved 13.43 W peak power at 88 W input power, resulting in a transfer efficiency of 15.26%. The use of an indoor laser based WPT system with a solar cell receiver at night was presented by Fakidis et al. (2016). They carried out OWPT system analysis in the absence of ambient light. Katsuta and Miyamoto (2018) reported an OWPT system with 15% efficiency using VCSEL and a GaAs solar cell. Recent studies reported more than 65% conversion efficiency using high power LDs with 940–980 nm wavelengths (Crump et al., 2013). The OWPT systems used in these studies were based mainly on LD, due to its key features of a narrow spectrum, low divergence, high directionality, and high power (Hecht, 2001). However, lasers also have some disadvantages. According to Japan's safety regulations for laser products, lasers are classified in different groups on the basis of their power level, emission duration, and wavelength (OMRON, 2022). Most laser hazards involve risks to eye safety. Thus, feasible light sources other than laser are needed. On account of its sufficiently narrow

spectrum, increased output power, improved efficiency, and low cost, a recent high performance LED (Optiwave Systems, 2022) based OWPT system can be considered as a good alternative. Zhou YH and Miyamoto (2019a) presented an LED-based OWPT system which is capable of delivering high electric power to compact IoT terminals. They obtained efficient power transfer using small GaAs solar cells and high intensity IR LED, and reported 200 mW output power at a transmission distance of 100 cm, with 41.7% solar conversion efficiency and 77% optical system efficiency.

Similarly, studies have confirmed that light collimation through passive optical elements such as lenses provides high directivity. Also, solar panels offer special potential for power harvesting from both a dedicated laser source and sunlight. Gray (2003) reported 100 mW/cm² irradiance from sunlight under standard test conditions (STC). Green et al. (2015) reported 12.3% efficiency for an amorphous silicon (a-Si) module at STC. They also estimated the efficiency of mono-crystalline silicon and multi-crystalline silicon (multi-c-Si) cells as 25.6% and 18.5%, respectively. Kinsey et al. (2011) reported the efficiency of amonix compound parabolic concentrator (CPC) solar power plants using concentrator PV technology. Green et al. (2015) reported 45.7% efficiency for a multi-junction cell using a concentrator. Fakidis et al. (2014) investigated the use of an OWPT system exclusively for indoor applications. They highlighted the use of an optical wireless (OW) link for energy harvesting and backhaul communication. The OW link was generated using a white LED, parabolic mirror, and Si solar panel. The harvested power was 18.3 mW and the link efficiency was 0.1%. In a follow-up study, they created an OW link using 1–5 red LDs, a collimated lens, and a multi-c-Si solar panel (Fakidis et al.,

2015). The calculated harvested power was 10.4 mW and the link efficiency was 0.74%. The reduced link efficiency was explained by the low efficiency of the solar cell and LD. The low level of harvested power was attributed to mismatch losses among solar cells and low optical power. Different OWPT systems used IR LEDs, EELs, and VCSELs. The different parameters of these optical sources are compared in Table 1. Table 2 summarizes research contributions to OWPT.

5 LED-based IoT-assisted OWPT

The information provided in this section reinforces our belief that IoT-assisted OWPT is a promising concept. We also briefly discuss the transmitter and receiver components for IoT-assisted OWPT systems.

IoT paves a way for various emerging applications in predictive maintenance, health monitoring, and smart cities. The IoT aims to connect ubiquitous devices to the Internet. Power supply is a key element to support communication and high-performance computation in IoT terminals. However, battery endurance is a major issue in battery-empowered IoT objects. There are two approaches for tackling this issue and increasing sustainability: improving battery charging techniques and enhancing the battery capacity. Enhancing the battery capacity can cause issues such as recycling, cost, weight, and safety. In this scenario, using WPT to enhance battery endurance seems the right approach. OWPT systems can be implemented in the context of wireless connectivity to IoT objects. An OWPT system designed like a portable flashlight device has been proposed in previous studies to power compact IoT terminals (Zhou YH and Miyamoto, 2019a). The device is small and simple,

Table 1 A comparison of the different parameters of optical sources

Optical source	Beam shape	Beam quality	Cost	Imaging	Packaging	Switching speed	Speckle	Spectral width (nm)	Modulation frequency
IR LED	Circle	Very wide divergence (180°)	Low	Low definition	Simple	Low	Low	20–30	Low
EEL	Elliptical	Medium divergence (~40°)	High	High definition	Complex	High	High	1–2	Normal
VCSEL	Circle	Low divergence (<20°)	Low	High definition	Medium	High	High in array	1–2	Very high

Table 2 Research contributions to OWPT

Reference	Transmitter	Receiver	Research goal
Zhou YH and Miyamoto, 2019a	High intensity IR LED	GaAs solar cell	Reporting 200 mW output power at a 100 cm transmission distance with 41.7% solar conversion efficiency and 77% optical system efficiency
Steinsiek, 2003	Green (532 nm), frequency-doubled Nd:YAG laser	Solar cell	Powering a mobile rover over a distance of 30–200 m
Hirota et al., 2015	975-nm VCSEL array	Si solar cells	Achieving 33% power generation efficiency of Si solar
Katsuta and Miyamoto, 2018	VCSEL	GaAs solar cell	Reporting an OWPT system with 15% efficiency
Crump et al., 2013	High power LDs with 940–980 nm wavelengths	–	Reporting more than 65% conversion efficiency
Fakidis et al., 2014	White LED	Si solar panel	The harvested power was 18.3 mW, and the link efficiency was 0.1%
Fakidis et al., 2015	Red LDs	Multi-c-Si solar panel	The calculated harvested power was 10.4 mW, and the link efficiency was 0.74%

and can be easily held by a drone, robot, or human. A small solar cell is used as a receiver, which can be put on IoT terminals. A commercially designed LED is used as the light source due to its large divergence angle, which gives high efficiency without any control system, through accurate irradiation. It is possible to target a small solar cell at a long distance (Liu WH and Feng, 2017). The above discussion shows that a proper system configuration is essential to obtain a target irradiation size and specific transmission distance. In previous studies, a 1-m transmission distance was achieved, which is suitable for charging various IoT terminals (Zhou YH and Miyamoto, 2021). The transmission distance can be increased through proper modification of the optical system configuration or possibly considering a larger device.

5.1 Optical transmitters for IoT-assisted OWPT

The maximum conversion efficiency of a solar cell is around the spectrum limit of the bandgap energy. The numerical expression for bandgap energy is given by

$$E_g = \frac{hc}{\lambda}, \quad (1)$$

where E_g is the bandgap energy, c is the velocity of light, and h is Planck's constant. As a GaAs solar cell has a bandgap energy of 1.424 eV at 300 K (Luque

et al., 2012), the related wavelength should be lower than 870 nm for IR LED. If the wavelength exceeds this value, then the quantum efficiency of solar cell will rapidly drop to zero. An IR LED with high intensity is required to obtain significant electric power in IoT OWPT systems. Moreover, a small divergence angle can lower the aperture of optical components and stop optical energy leakage. A 2 mm×2 mm single-chip LED can provide a small irradiation area. In existing commercial market products, the highest intensity is 1 W for IR LEDs of 2 mm×2 mm or smaller. These LEDs have a divergence angle from a few degrees to a hundred degrees (Hecht, 2001). An 810-nm (OSRAM, SFH-4703AS) IR LED with a ±40° divergence angle and 1.04 W intensity was implemented in previous studies of OWPT systems. Researchers successfully obtained 41.7% PV conversion efficiency. The electrical output from a GaAs solar cell was 223.9 mW and the total efficiency of the OWPT system was 6.3%.

In any OWPT system, the incident light rays are targeted on a small receiver from a long distance, requiring perfect accuracy of irradiation. To achieve high efficiency also requires a proper lens system. Researchers used a multi-lens system to achieve the divergence angle described above. The lens system combined the use of an aspheric condenser lens and a Fresnel lens. The aspheric condenser lens was used to control divergence to minimize the aperture of the

Fresnel lens and optical energy leakage. The purpose of the Fresnel lens was to construct a large aperture using a small lens. Although the imaging performance of a Fresnel lens is no better than that of a convex lens, it can be efficiently used for IoT-based OWPT applications.

5.2 Optical receivers for IoT-assisted OWPT

A solar cell is considered the best energy harvester in an OWPT system. Its semiconductor material is capable of converting optical energy into electric power under a PV effect. Commonly available solar cells are GaAs and Si solar cells. Although Si solar cells are cheaper, GaAs cells are preferred because of their high efficiency, based on their lightweight properties and high bandgap energy. Therefore, GaAs solar cells are usually selected, and researchers are working on their cost reduction due to their rapidly growing applications. If an LED requires a narrow spectrum, then a multi-junction solar cell (Yamaguchi, 2003; Green et al., 2015) is not required to cover a broad range of spectrum. A low-cost single-junction GaAs solar cell matching the wavelength of an LED is appropriate to achieve high efficiency. Solar cells of 5 cm×5 cm or larger do not satisfy the requirements of IoT applications, and solar cells below 1 cm do not fulfill the power requirements of IoT terminals, which need dozens of mW power (Nguyen and Chapman, 2020). Zhou YH and Miyamoto (2019a) from Tokyo Institute of Technology, Japan demonstrated an OWPT system for compact IoT terminals using a 1.7 cm×1.7 cm lightweight and flexible GaAs solar cell (Fig. 12).

6 OWPT techniques

The main focus of this section is to highlight different OWPT techniques such as optical beamforming, DLC, ADLC, and SLIPT. We also discuss research efforts dedicated to each technology.

6.1 Optical beamforming

Optical beamforming is the technique in which light from an optical source is focused on a receiver device. It enables wideband signal transmission and prevents beam-squint and imbalance loss effects. The

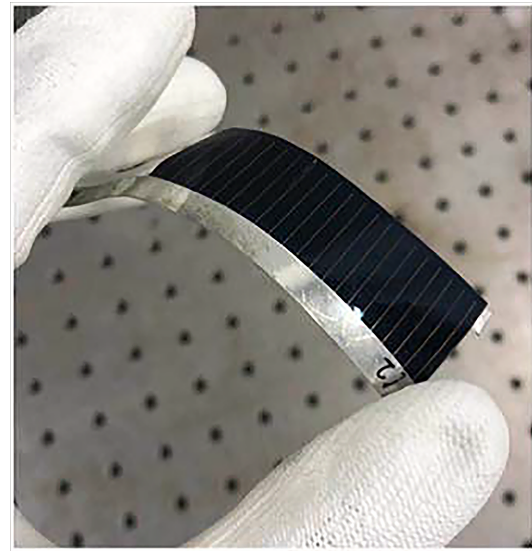


Fig. 12 A thin and flexible GaAs solar cell used in an OWPT system (Zhou YH and Miyamoto, 2019a)

block diagram of optical beamforming is illustrated in Fig. 13. An LED or LD is used as an optical source and a solar panel is used as a receiver. A spatial light modulator (SLM) is used for LD light beamforming. An SLM is used to modulate the phase or intensity of LD light at each pixel. As an SLM can modulate light spatially in phase and amplitude, it acts as a dynamic diffractive module. The beam-formed light is precisely incident on the solar panel, and then optical energy is delivered from the optical source to the intended object. The SLM should recognize the exact position of the intended object. A beam expander can be added to expand the laser beam size, while it can be omitted in case of an LED. Some SLM models also require a polarizer to modulate the phase of light. A Fresnel lens function controlled with a computer is used to operate an SLM as a dynamic focusing lens. After focusing the beam-formed light to the screen, optical energy is transferred to the receiver solar cell.

Kim SM and Won (2013) proposed an optical beamforming algorithm which can automatically trace

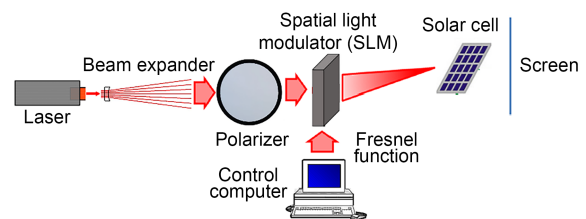


Fig. 13 A block diagram of optical beamforming

the position of an intended device. In this technique, LED-based visible light communication (VLC) and a solar cell receiver based device were used for a download communication link, while RF-based wireless communication, e.g., Wi-Fi or bluetooth, was used for an uplink communication link. They also repeated their experiments using red and green LEDs. Using this technology, they obtained 50%, 40%, and 36% optical beamforming efficiency for green laser, red laser, and white LED, respectively. Fakharzadeh et al. (2008) demonstrated optical beamforming for targeting indoor a white LED on a receiver target. They proposed a robust, fast, and accurate algorithm to tune the coupling factors of parallel ring resonators to create the target delay for optical beamforming of the transmitter arrays. Recently, the US Navy made a breakthrough trialing optical beamforming for naval communications. It will test optical beamforming for use in challenging environments at sea. Isotropic Systems, a well-known manufacturer of broadband terminal technology, has a contract with the defense innovation unit (DIU) (Messier, 2020) to design and test a new optical beamforming system (Fig. 14) for reliable operation in harsh environments including intense wind, EMI, and salt water.



Fig. 14 An optical beamforming antenna made by Isotropic Systems (Meller, 2020)

6.2 Distributed laser charging

During the transformation of electronic devices to wearable devices, desk phones to smart phones, and desktops to laptops or tablets, mobility has become a critical challenge. IoT and mobile devices like smartphones and sensors are powered by batteries with short operation times. It is difficult to charge IoT sensors installed in harsh environments, such as volcanoes and underwater environments. Carrying a

power cord and finding a power socket to recharge mobile devices can be difficult and disruptive. Therefore, a viable solution that has emerged is the wireless charging of mobile devices with the potential to replenish the battery over the ether. It offers various benefits such as user convenience, product durability, usage flexibility, and on-demand availability (Lu X et al., 2015). Here, WPT appears to be a good alternative approach to support perpetual energy supplies. Different WPT technologies are suitable for various application scenarios, but it is still difficult to charge IoT devices including drones, laptops, smartphones, and smart sensors over a long distance. To overcome this challenge, DLC (Liu QW et al., 2016) has emerged as a promising wireless charging technique.

DLC, also referred to as spatially distributed laser cavity resonance, is commercially available and has emerged as a practical light-aided charging technology. According to relevant Patent Cooperation Treaty (PCT) patents (US8525097B2 and US9225140B2) (Kim SM and Won, 2013), this technology can be summarized as follows: retroreflectors are used in the receiver component for the reflection of the incident beam from a transmitter and the detection of the transmitted optical beam path back at the transmitter. This supports the ability to adjust tunable beam parameters. The power flow due to resonance is stopped in case of unavailability of a line-of-sight (LOS) path between transceivers.

The DLC technology offers self-alignment to charge IoT devices without any special positioning and tracking, as long as an LOS path is present between the transceivers. A small DLC receiver can be easily embedded into a sensor or smartphone or sensor, and a transmitter can be attached to a ceiling. In addition, a single DLC transmitter has the capability to charge multiple devices simultaneously (Gong et al., 2013). As a DLC system uses PV cells rather than a collecting lens, it is a more practical, lightweight, and cost-effective approach than using traditional heavy batteries.

Fig. 15 shows an innovative mechanism to charge mobile electronic devices through DLC. In Figs. 15a and 15b, DLC transmitter 1 with an LED array is used to design a DLC-assisted lightbulb. This DLC transmitter can be easily integrated to the wall or ceiling to charge mobile devices located in its proximity. In another case, a DLC transmitter is embedded

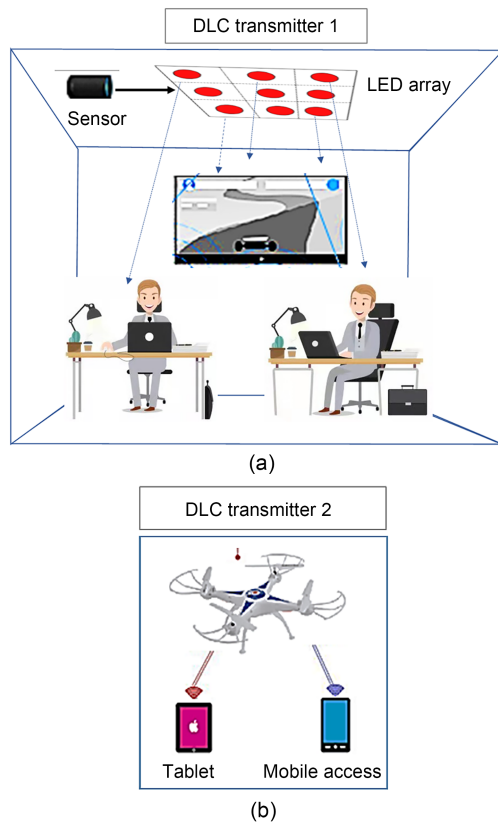


Fig. 15 DLC potential applications: (a) LED array transmission; (b) drone transmission

into a drone which can be used to charge IoT devices such as mobile phones and tablets. A DLC receiver is also integrated to the drone. Hence, DLC transmitter 2 can also recharge it. Note that the efficiency of the DLC system is severely impacted by various

parameters such as laser wavelength, laser transfer attenuation, and electricity-to-laser and laser-to-electricity conversion efficiency (Hu et al., 2020). Zhang QQ et al. (2018) introduced a multi-module DLC architecture and comprehensively discussed the evaluation of power conversion or transmission for each module, considering the effects of laser wavelength, attenuation, PV cell, and temperature. Liu QW et al. (2016) briefly explained the DLC technique for safe mobile applications. They proposed two wireless charging techniques: a DLC-assisted infrastructure based network and a DLC-assisted ad-hoc network. Similarly, Wi-Charge obtained about 2 W power at a distance of 10 m to simultaneously charge several smartphones and laptops. Wang W et al. (2019) also demonstrated resonant beam charging (RBC) for IoT objects and achieved 2 W power at 2.6 m distance. Fang et al. (2019) proposed a first-access first-charge (FAFC) scheduling algorithm to enhance WPT performance for multiple IoT objects by improving charging efficiency, prolonging charging time, increasing transmitted power, and restricting the number of receivers. To the best of our knowledge, several research groups have explored this technology, but commercial products have not yet been disclosed. Table 3 summarizes a comparison of DLC with different WPT techniques.

DLC provides various advantages over other LPT techniques including access control, compact layout, and a long transmission distance. However, DLC also has some potential drawbacks such as propagation

Table 3 A comparison of different WPT techniques (Liu QW et al., 2016)

WPT technique	Advantage(s)	Disadvantage(s)	Charging distance	Application(s)
Inductive coupling	Simple implementation, safe	Alignment issues, heating effect, short charging range	Up to a few centimeters	Contactless smartcards, RFID tags, mobile electronics
Magnetic resonance coupling	Non-line-of-sight (NLOS) charging, high charging efficiency, charging multiple devices	Complex implementation, limited charging distance	Up to a few meters	Electric vehicle charging, home appliances, mobile electronics
Microwave radiation	Longer charging range	Low charging efficiency, health and safety issues in high exposure	Up to several kilometers	LEDs, implanted body devices, sensors, RFID cards
Distributed laser charging (DLC)	Suitable for mobile applications, SLIPT and LBS ready, visibility agnostic, EMI free, safe, self-alignment	Low charging efficiency, LOS required	Up to several meters	LEDs, sensors, consumer electronics, mobile devices

attenuation, DLC receiver tracking, power conversion efficiency (PCE), laser hazard, quality-of-service (QoS), inherent LOS dependence, and DLC transmission distance under path-loss constraints. Some features (Liu QW et al., 2016) of DLC are as follows:

1. EMI-free: In DLC, there is no leakage of power outside the resonating beam. It does not impose RF radiation like other WPT techniques.

2. Compact layout: In DLC, a compact receiver such as smartphone camera is used, which is suitable for the beam diameter of one millimeter.

3. Visibility agnostic: DLC can rely on visible as well as IR and ultraviolet (UV) lasers. This visibility agnostic characteristic of DLC makes it flexible and reliable for various applications.

4. Concurrent wireless charging: When a receiver comes across the LOS link of the transmitter, the DLC system creates a resonating beam. Thus, a single transmitter has the potential to generate multiple resonating beams pointed towards different receivers, which ensures concurrent charging of multiple receivers from a single transmitter.

5. Intrinsic safe: In case of a high power level up to dozens of watts, the DLC system raises safety concerns. However, DLC is unique from integrated resonating lasers due to the spatially distributed resonator architecture. Whenever an object appears into a resonating beam path of the DLC system, the laser is curtailed quickly without any extra decision-making circuit.

6. Self-aligning: In DLC, the charging process remains active until the LOS path remains between the transceiver elements. In such a situation, the distributed resonator has the capability to generate a resonating beam without any aiming or tracking features.

Liu QW et al. (2016) presented different features of DLC including intrinsic safety, self-alignment, and concurrent charging (Fig. 16).

6.3 Adaptive distributed laser charging

In DLC, battery overcharging can lead to thermal effect, energy waste, and safety concerns, while uncharging may cause capacity reduction and charging time extension. DLC is similar to WPT technology, and it can provide constant power to charge any battery. However, some batteries, such as the commonly available Li-ion batteries, require variable current and voltage. Therefore, dynamic power is required

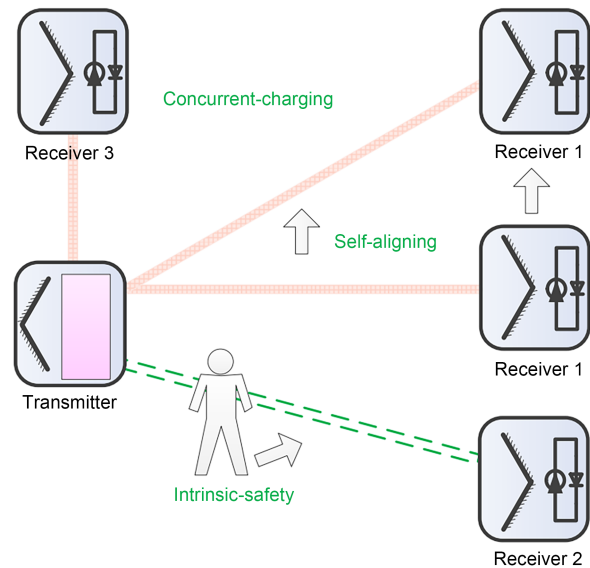


Fig. 16 Distributed laser charging (DLC) features (Liu QW et al., 2016)

for the optimization of battery charging performance and capacity maximization. Therefore, a DLC system cannot optimize both battery charging performance and transfer efficiency. For a Li-ion battery, a slight undercharging can reduce capacity while overcharging can cause damage. It requires power control for security and optimal performance. To solve these problems, an alternative solution is ADLC or adaptive resonant beam charging (ARBC). It is similar to link adaptation in wireless communication, which is used to optimize information delivery. In ADLC, adaptive power is transmitted on the basis of feedback information from the ADLC receiver. The ADLC technique can significantly enhance energy use. There have been several studies of battery charging optimization to control power dynamically to provide the required charging values. According to Zhang QQ et al. (2019a), the adaptive mechanism in DLC can save up to 61% of energy in battery charging. Zhang QQ et al. (2019b) applied the ARBC technique to provide perpetual energy to EVs in Internet of Intelligent Vehicles (IoIV). Zhang QQ et al. (2017) also demonstrated an ARBC system to optimize both battery charging performance and transfer efficiency. They analyzed ADLC's power conversion to evaluate performance and saved 60.4% of energy compared to a conventional constant power charging mechanism. Xiong et al. (2019) introduced a time division multiple

access (TDMA) based scheduling algorithm, which provided flexible driving power control, individual user power control, constant driving power, concurrent charging, and continuous charging features. TDMA-based WPT inspires this concept of improving ADLC systems, such as quality of service and flow control.

Fig. 17 presents the basic block diagram of an ADLC system, which is based on a power supply and gain medium at the transmitter site and a PV cell, battery, and a DC-to-DC converter at the receiver. The feedback system is based on a power controller and power monitor. The power monitor is used to track the battery current and voltage. The required laser power is determined by the PV cell output power and battery charging profile. The feedback information system can be designed to use infra-communication, bluetooth, or Wi-Fi. The power controller at the transmitter is used to handle the feedback information. It is used to simulate different powers on the gain medium to create variable resonating beam power. There are several challenges in ADLC which must be investigated in the future. For instance, the temperature effect on the system and the effect of resonating laser beam propagation loss must be evaluated (Zhang QQ et al., 2017).

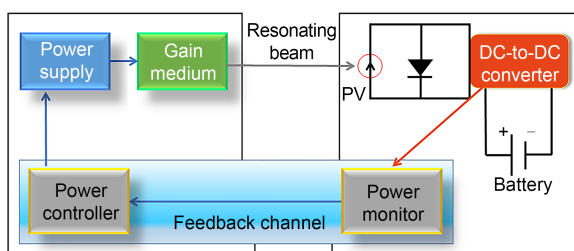


Fig. 17 Block diagram of an adaptive distributed laser charging (ADLC) system

6.4 Simultaneous lightwave information and power transfer

Some studies have demonstrated the idea of SLIPT, in which networking and communication modules are incorporated within the DLC transceiver. Both visible and invisible light-aided communication methods can be implemented with the assistance of DLC to realize SLIPT (Zhang R and Ho, 2013; Zhang R et al., 2015b). Moreover, both WPT and control signaling can be incorporated in a single resonating

beam without any dependency on radio communication, like bluetooth or Wi-Fi. SLIPT offers the advantage to transmit information and power simultaneously. However, SLIPT can be a source of interference and RF pollution to data transfer. One viable approach to overcome RF shortcomings is to harvest energy from LEDs and LDs. Through an optical source, simultaneous data and energy transfer can be achieved. This strategy is mooted as a key enabler to wirelessly recharge batteries of the IoT, Intelligent Internet-of-Things (IIoT), and Internet of Underwater Things (IoUT). Researchers modified this idea calling it SLIPT (Diamantoulakis et al., 2018). Recently, SLIPT has obtained significant interest as a promising technique to support WPT between communication terminals. It is a cost-efficient approach for wireless systems, e.g., remote sensors and autonomous self-powered devices.

The idea of SLIPT has been demonstrated for indoor IoT applications and powering of IoUT devices (de Oliveira Filho et al., 2020). SLIPT can be implemented through indoor VLC (Ma et al., 2019) and IR communication using a solar panel as the receiver. Pan et al. (2019) investigated SLIPT for secure communication, hybrid VLC-RF, and multiple-input multiple-output (MIMO) techniques. Recently, Fakidis et al. (2020) performed SLIPT for 1 Gb/s GaAs VCSEL and PV link, which has significant importance for next-generation backhaul connectivity. Through precise optimization, it is possible to achieve significant gains in power transfer, spectral efficiency, interference management, and reducing time delay and energy consumption. This technique also provides a significant trade-off between rate and harvested energy (Diamantoulakis et al., 2017). MIMO VLC (Fig. 18) can be used in MIMO SLIPT VLC to achieve a suitable trade-off among cost, data transmission, and energy harvesting (Pan et al., 2019).

6.4.1 SLIPT for IoUT

Recently, SLIPT has been proposed for powering IoUT devices. The motivation behind this is the rapidly growing demand for underwater communication systems because of ongoing expansion of marine activities such as offshore oil field monitoring, undersea earthquake monitoring, scientific data collection, underwater exploration, marine current power grid

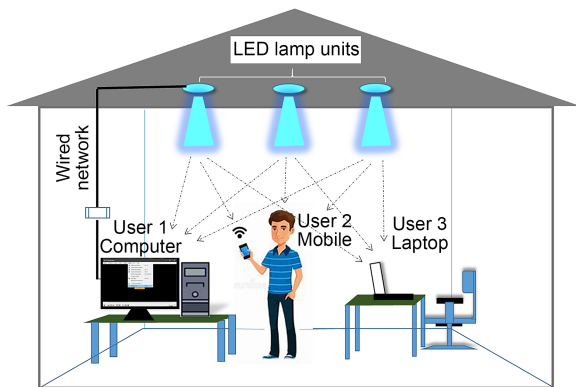


Fig. 18 Multiple-input multiple-output visible light communication

connections, pollution tracking/control, and marine life observation. Underwater data transmission can be achieved using optical, radio, and acoustic waves. Generally, acoustic communication is used for underwater applications as it can cover several kilometers. The associated frequency range for acoustics is 10 Hz to 1 MHz. However, it is prone to limited bandwidth, low propagation speed, and high latency. Moreover, RF waves can propagate over a large distance with low frequencies (30–300 Hz) and suffers badly from attenuation. RF waves are not sufficient for practical applications as they need high power and large antennas. In contrast, underwater optical wireless communication (UOWC) provides high transmission data in several Gb/s with large bandwidth. SLIPT has emerged as a complementary technology to UOWC for both wireless charging and continuous connectivity in harsh ocean environments. Multiple theoretical and experimental SLIPT studies in free space have been reported, but only a few have discussed underwater media. SLIPT in underwater media is yet to be explored. In a previous study, an underwater communication link was designed with a 5 cm² solar panel as the receiver in a 7 m long water tank. Kong et al. (2019) demonstrated a VLC system using AquaE-lite, white laser, and Si thin film solar cells in 20 m of air and 2.4 m of turbid poor water. de Oliveira Filho et al. (2020) reported energy harvesting and communication scenarios in an underwater environment. Charging was achieved by light beams emitted from a boat or autonomous underwater vehicle (AUV). The battery of a submerged module can be recharged by turbidity or temperature sensors. The major issues in deploying SLIPT-based underwater devices are pointing,

acquisition, and tracking (PAT) requirements, but these can be minimized using a solar cell as a photo-detector. A much greater research effort is needed from the research community to overcome channel-related issues and other major technical challenges before wide-scale underwater deployment can be achieved.

6.4.2 Open issues in SLIPT

There are several challenges related with different SLIPT techniques, which are associated to either a propagation effect over wireless underwater media or the hardware, such as battery lifetime and the bandwidth of the solar cell. Here we discuss open issues and propose solutions for future research directions.

1. LOS issue. One of the critical challenges for underwater SLIPT is an obstructed propagation path. This can be removed by enhanced UV scattering to establish an NLOS path. However, it needs a solar-blind solar cell for energy harvesting from UV light. A deep understanding of this technique is required to tackle safety challenges from UV exposure.

2. Beam divergence. During propagation in an unguided medium, the light beam diverges. This leads to an increase of radius. Losses because of beam divergence are referred to as geometrical attenuation. Such losses are related to the LED or LD source, operating wavelength, and propagation distance. Beam divergence must be taken into account for SLIPT systems. The designed system should maximize the capture of incident light, and received power must fulfill both the communication and power transfer functions of SLIPT.

3. Propagation effects. As light propagates through water, the light intensity decreases exponentially. A light beam can also face turbulence, which is due to air bubbles, salinity variation, and temperature fluctuations. Salinity variation and temperature inhomogeneity cause rapid variation in the refractive index of water, while air bubble can partly or fully block a light beam. Some studies have proposed statistical channel modeling to find the impact of turbulence on UOWC systems. To perform SLIPT functions in an underwater channel, turbulence and attenuation must be taken into account for high performance of both SLIPT functions. The impact of turbulence can be reduced using multiple wavelengths for energy harvesting and communication purposes. Continuous

connectivity of devices can be achieved using different wavelengths. Different wavelengths can be used to send different data streams and a power splitting approach can be used for battery charging.

4. Hardware challenges. Another limiting factor for SLIPT performance is the bandwidth of the receiving component. The bandwidth of commercially available solar cells is limited to dozens of kHz. The restriction on the data rate can be alleviated using advanced modulation schemes, like Mary quadrature amplitude modulation (M-QAM) orthogonal frequency division multiplexing (OFDM). In addition, the transmission capacity can be improved by a power splitting SLIPT approach in which a PD is used at the receiver instead of a solar cell. A high bandwidth PD can be used at the expense of a pointing error, as it has a small detection area compared to a solar cell. Additional hardware challenges are associated with the battery lifetime of IoUT devices.

6.5 Fly-eye lens system for OWPT

Katsuta and Miyamoto (2019b) constructed a fixed OWPT system to transmit 10 W power over a 2 m transmission distance. They added a fly-eye lens to the OWPT system, and developed a technique for solar cell irradiation with multiple optical sources of high frequency. Previously, they had reported work on optimization of the fly-eye lens system (Katsuta and Miyamoto, 2019a). In their proposed configuration, a solar cell was attached with a fly-eye lens. A high-power single-chip VCSEL array was used as it was commercially available with 20–40 W output power. A fly-eye lens system contained several small single lenses in the form of a 2D array (van Giel et al., 2007). A schematic of the fly-eye lens system can be seen in Fig. 19. By embedding a pair of fly-eye lenses, the incident optical beam over the fly-eye lens was split by the array lens, and then the imaging lens was

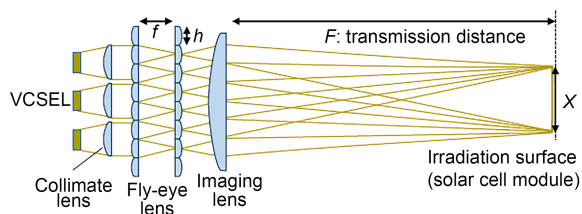


Fig. 19 Overview of a fly-eye lens system in OWPT (Katsuta and Miyamoto, 2019b)

used to image the beam on the irradiation surface. In the proposed system, uniform intensity distribution can be achieved by irradiating light of a similar geometry to a single lens. In this fly-eye lens system, various optical sources can be used and each optical source was at an arbitrary position. Due to this characteristic, fly-eye lenses were used for semiconductor manufacturing equipment and projectors (Kasazumi et al., 2004). In an OWPT system, a fly-eye lens appears to be a promising approach to obtain uniform intensity distribution and a rectangular irradiation pattern at a distant point from an optical source, with high efficiency.

Katsuta and Miyamoto (2019b) have presented a fly-eye lens system with a different configuration. As in an OWPT system, light leakage occurs outside the solar cell, which decreases the transfer efficiency. Therefore, a precise alignment between transmitter and receiver modules is needed. This causes an increase in the expenditure of installation and degradation of performance because of misalignment through aging. By designing a system to maintain tolerance of positional misalignment, it is possible to overcome aging deterioration and alignment precision. A passive mechanism is required, as this configuration becomes complex while using an active mechanism. The proposed configuration involves an optical system of a fly-eye lens incorporated with a solar cell (Fig. 20). In this configuration, light irradiation is achieved within the size of a fly-eye lens, and transmission distance is not dependent upon the focal length of the imaging lens. This use of a fly-eye lens in an OWPT system provides uniform irradiation and reduces light leakage outside the solar cell. This results

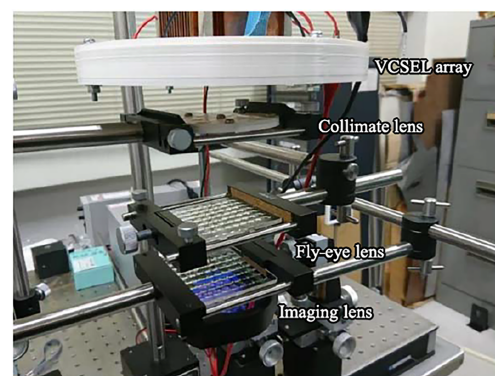


Fig. 20 Experimental demonstration of the fly-eye lens (Katsuta and Miyamoto, 2019b)

in an effective method to expand usage conditions, and can support the installation precision required for an OWPT system. This structure can enhance the allowable incident angle and positional shift, and can adjust the transmission distance.

6.6 OWPT system by spatial wavelength division and distributed laser cavity resonance

Spatially distributed laser cavity resonance is a promising solution for optical charging systems. In this scheme, optical power is transmitted over a 2D field of view using two orthogonal diffraction gratings. This scheme allows wavelength bands to be distributed to optoelectronic devices across space (Oh et al., 2016). A diffraction grating is used in the transmitter part to spatially disperse the light from a semiconductor optical amplifier (SOA). At the receiving unit, multiple resonant cavities are formed using retro-reflecting beam splitters to reflect the incident beam back to the transmitter. Retroreflectors tap power from the resonant cavities by enabling a user-friendly alignment. An automatic safety mechanism can be incorporated to cease the cavity resonance if any vulnerable object breaks the LOS between the transmitter and receiver candidates. A drawback of this technique is the limit to high power radiated by the maximum permissible exposure (MPE) defined by the International Electro-technical Commission (IEC) (IEC, 2007). A spatially distributed resonator laser system was reported which has a planned path to commercialization. According to relevant PCT patents (US8525097B2 and US9225140B2) (Kim SM and Kim, 2013a), we can summarize this technology as follows: a light beam is reflected using retro-reflecting components in the receiver element, and retraces the

incident light beam path back to the transmitter component. It supports the addition of components within the cavity to configure beam parameters or amplification. When the LOS path between transceivers is blocked, power transmission is immediately stopped. When the path is restored, high optical power is transmitted to distant receiver components. As a proof-of-principle, Lim et al. (2019) carried out experiments for DLC by merging the ideas of distributed laser cavity resonance and diverging angular dispersion. They used an SOA to enable a broadband gain spectrum, a diffraction grating for angular dispersion of IR light of different wavelengths, and a retroreflector to reflect the light beam to the SOA to establish a resonant cavity. The proposed OWPT system is shown in Fig. 21. This OWPT system employs diverging angular dispersion and distributed laser cavity resonance to enhance the WPT, with fewer hazards. The system is based on the use of a transmitter unit to accommodate multiple receiver units. A gain medium is used to amplify power, a diffraction grating for angular dispersion, and a telescope to distribute it over a wide field-of-view (FOV). The receiver includes a retro-reflecting beam splitter to reflect a narrowband light to the transmitting unit, developing a resonant channel which stimulates laser excitation. In the case of hazard-prone objects interfering with the LOS, a safety mechanism is incorporated to reduce the power emission from the transmitter. With FOV optimization and careful retroreflector design, this novel design can be exploited for commercialization.

6.7 OWPT-based rapid charging

Raavi et al. (2013) presented an OWPT system to deliver power to mobile portable devices. The system

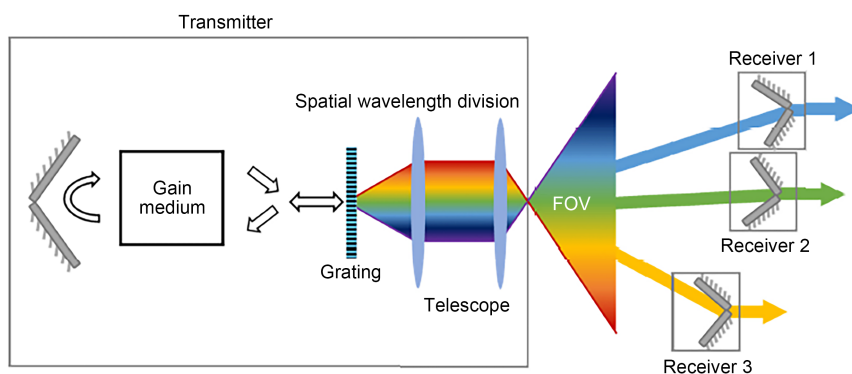


Fig. 21 A schematic of the proposed OWPT system (Lim et al., 2019)

contained an optical antenna, a DC-DC converter, and a commercially available GaAs solar cell. A nano-structured optical antenna embedded with a GaAs solar cell expedited the charging process to employ a plasmonic electric field enhancement effect. A single-junction GaAs solar cell was developed to achieve high efficiency, while maximizing the output power. A step-up DC-DC circuit was used to obtain the required DC voltage and stable current from the solar cell for recharging batteries of portable devices. It was an efficient, compact, and secure OWPT system. This system can achieve fast and smart charging over long distances, while ensuring high efficiency and compliance with human safety regulations. The proposed OWPT system is presented in Fig. 22. The optical sources are attached to the room ceiling and emit light beams compliant with FCC human safety regulations. The central station linked with the optical sources receives the pilot signal from charging devices and adjusts the activation and deactivation process of optical sources. The mobile devices to be charged contain an optical antenna embedded with a solar cell and a DC-DC circuit. These devices can be installed at any point in the room to receive optical energy.

An innovative technique for rapid charging is to amplify the power density of light using a PV semiconductor device with an optical antenna. GaAs is selected due to its high efficiency and absorption coefficient. In this solar cell structure, both the p-AlGaAs window layer and n-AlGaAs layers reduce

the surface recombination. An anti-reflection coating is required to suppress the reflection, which can be as higher as 20%–30%. The photon confinement by the optical antenna can reduce the emitter and base thickness to enhance the efficiency of excited minority carriers. The amplification achieved by the optical antenna is 2–3 times higher and is not restricted by the principles of geometrical optics. A performance comparison with and without an optical antenna is shown in Fig. 23, which indicates a clear increase in output power.

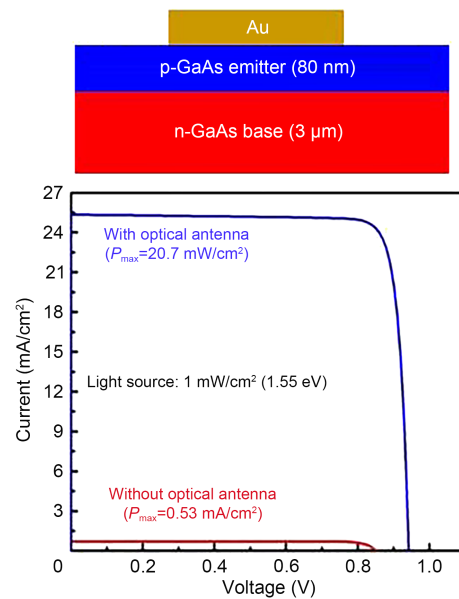


Fig. 23 Maximum output power from a single-junction GaAs solar cell incorporated with and without an optical antenna (Raavi et al., 2013)

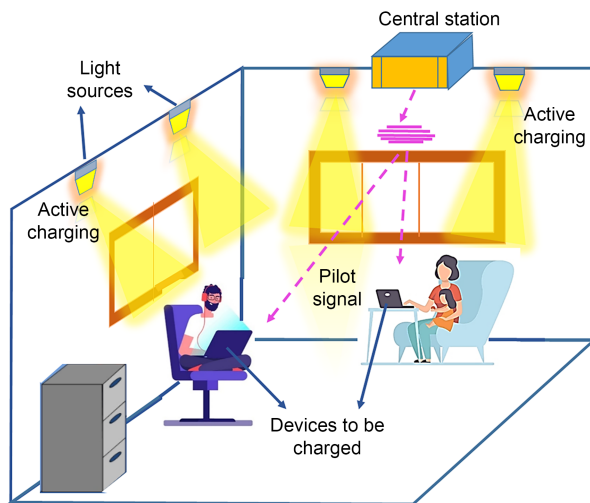


Fig. 22 A schematic overview of the wireless energy transfer system

6.8 Thing-to-Thing OWPT

Recently, Nguyen et al. (2020) have demonstrated a novel OWPT system for objects, either mobile or stationary. Unlike existing OWPT systems, in which the transmitter and receiver are two different devices, this novel conceptual system deploys only a single device (optical transceiver), which performs both tasks of light absorption and emission. In this proposed system, things/objects are partly or fully covered by perovskite transceivers to enable wireless charging or discharging functions. This idea removes the unidirectional WPT limitation and supports bidirectional OWPT between both mobile and stationary objects. The proposed OWPT system is presented in

Fig. 24. The system is composed of a transmission medium, e.g., air, outer space, or seawater, and devices on which optical transceivers are deployed. The optical transceiver is fabricated from lightweight, thin, flexible, and low-cost metal halide perovskite. The flexibility characteristic of a perovskite transceiver makes it adaptive to any surface. Metal halide perovskites offer several advantages including compatible to low-cost solution processing, bandgap tunability, high absorption coefficients, large carrier diffusion lengths, and high carrier mobility. The maximum PCE of perovskite solar cells is 25.2% (Park and Zhu, 2020). Moreover, perovskites can be used as emitters of LEDs due to their efficient photoluminescence feature. Recently, over 20% external quantum efficiency has been reported with perovskite LEDs (Lin KB et al., 2018).

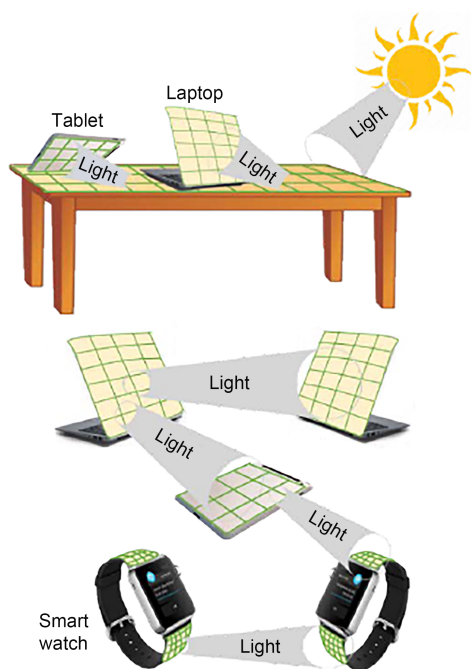


Fig. 24 The proposed T2T OWPT system (Nguyen et al., 2020)

6.9 High intensity laser power beaming

HILPB is a promising technique for long-range WPT for both terrestrial and space applications. In an HILPB system, a high-power LD source is used because of its excellent characteristics of small size, high reliability, and high efficiency. A schematic block diagram of HILPB is shown in Fig. 25. The transmitter

converts power into a monochromatic light beam through an LD. This laser beam is directed towards a solar panel via a beam director. At the receiver, the optical signal is converted to electric power. In practical HILPB systems, the system performance is restricted by the conversion efficiency of the light source and receiver. Since each component has a fundamental role in the overall system efficiency, high-performance components are chosen for designing an efficient system.

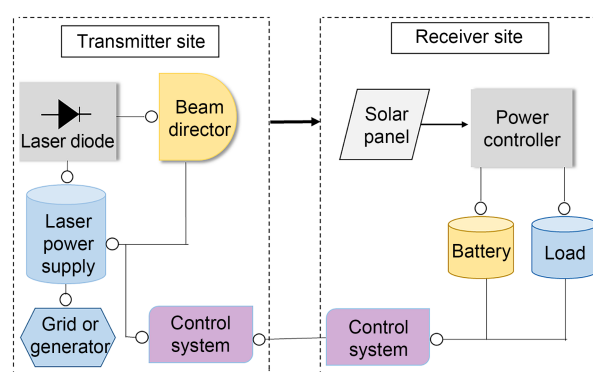


Fig. 25 A schematic of a high intensity laser power beaming system

HILPB technology is capable of transmitting energy to remote mobile devices, e.g., robots, UAVs (Raible, 2008), and satellites (Nayfeh et al., 2011). It can be used for optical refueling of resource-constrained platforms which use electrical energy as sources of propulsion and capability. In addition, HILPB has the ability to connect power plants, landing sites, and lunar habitats. The extensive applications of the HILPB system make it an attractive endeavor for a complete WPT system, but every component must ensure high end-to-end efficiency. There was little research interest in HILPB until a variety of LPT projects were developed in the 2000s. Steinsiek (2003) designed a laser-based minirover for space exploration missions. They demonstrated this project with an Nd:YAG 532 nm laser with 5 W output power. An orthogonal angle between the laser beam and the PV cell was maintained through a tracking system over a 280-m distance. Then, in 2003, researchers from NASA demonstrated a laser-based aircraft flight (Raible, 2008). The aircraft was fitted with 1.5 kW diode at 940 nm and a thin film PV array. Researchers from Kinki University, Japan developed a laser-based

small airplane (Kawashima et al., 2007), and a laser-based robot (Kawashima and Takeda, 2008). Becker et al. (2010) designed an HILPB-based robot climber for the NASA Centennial Challenges. He et al. (2014) from Beijing Institute of Technology, China demonstrated a laser-based WPT system operating at 100-m distance using a PV converter. In 2016, Russian scientists successfully implemented cell phone charging at 1.5 km using a laser and PV converter. The Russian Academy of Cosmonautics intended to apply this LPT technology to military vehicles and satellites (Jin and Zhou, 2019). Table 4 summarizes some HILPB systems.

7 Transceiver selection in OWPT

In this section, we discuss hardware technologies, such as laser and PV cells, which enable OWPT. In our end-to-end discussion, the appropriate selection of these components is important. Understanding these devices and their capabilities is crucial for designing an efficient OWPT system.

7.1 Laser selection

The American National Standard for Safe Use of Lasers (ANSI Z136.1) (Rockwell et al., 2015) provides instruction for the installation, safe operation, maintenance, and service of lasers for optical communication systems. It gives guidelines for laser selection and safety operations throughout the USA, including the market, government, and academic sectors. The above reference contains important information about laser selection, safety concerns, and standard operations. Currently, different types of lasers are commercially available. Accurate selection of the laser must comply with several constraints including (1) OWPT through different environments and (2) the maximum target transfer energy. The transmission medium

requires selection of a laser with an appropriate wavelength. The laser must operate with maximum energy transfer for the high performance of any OWPT system. Duncan (2016) reported laser-empowered element selection in which the 780 nm and 1100 nm regions were appropriate for commercially available laser technologies. Similarly, the spectral windows of 800, 900, and 1500 nm are preferred for power beaming to UAVs. The main factors of lasers contain:

1. Directionality: Generally the laser light provides a low divergence (Silfvast, 2004).
2. Coherence: The emitted photons show constant phase coherence.
3. Monochromaticity: A laser beam contains a narrow range of wavelengths.

Table 5 summarizes existing laser technologies, and presents different laser types which support beaming in dozens of kilowatts (Mason, 2011). The diode-pumped solid-state lasers (DPSSLs), like disk and fiber lasers, are good for high-power and long-range LPT systems as they support both beam quality and high power. A few high-power lasers are commercially available (Iwai et al, 2009; Alsulaiman et al., 2014). On the other hand, high-power LDs are more compact, cost-effective, and efficient as compared to DPSSLs. In addition, safety concerns are essential while performing LPT experiments. Most lasers are hazardous for human skin and eyes. An LPT system with low power levels can also pose a safety risk, and thus it is challenging to design a hazard-free in-house charging system (IEC, 2007; Sahai and Graham, 2011). Computer models have been developed to predict the injury threshold at different wavelengths (Jean et al., 2021). Table 6 summarizes eye safe lasers, and Table 7 summarizes the related standards for eye safety of laser products (Soltani et al., 2021).

A high-efficiency high-power semiconductor light source is effective as an optical transmitter for OWPT

Table 4 Different high intensity laser power beaming systems

Reference	Laser type	Wavelength (nm)	Cell type	Distance (m)	Efficiency (%)
Raible, 2008	Diode 1.5 kW	940	Si	15	<8.5
Kawashima and Takeda, 2008	Diode 400 W	808	GaAs	50	<14
Becker et al., 2010	Disk 8 kW	1060	Si	1000	1.25
He et al., 2014	Diode 25 W	793	GaAs	100	11.6
Ortabasi and Friedman, 2006	Nd:YAG	1060	Si	3	<14

Table 5 Existing laser technologies (Mason, 2011)

Laser type	Wavelength (nm)	Efficiency (%)
Diode 10 kW	850	50
Fiber 10 kW	1060	25
Fiber 20 kW	1060	25
Thin disk 25 kW	1060	25

systems. LD is preferred to generate collimated light. The other optical sources have low power conversion efficiencies, except LED. Some LEDs are also more efficient than LD, but their light use efficiency is still limited. An interesting optical source for an OWPT system is a VCSEL (Fördös et al., 2018). It has characteristics of a scalable array size and optical output by 2D array (Seurin et al., 2013). Moreover, a VCSEL is preferred for catastrophic optical hazard-free operation (Moser and Latta, 1992). Commercially available GaAs and Si solar cells are suitable for its beam reception. Reported efficiencies of EELs and VCSELs are presented in Fig. 26. A plot of the historical power conversion efficiencies of VCSELs is presented in Fig. 27. Semiconductor lasers (Welch, 2000) are the subject of extensive research and their efficiency has been dramatically improved by up to 70% at around

the wavelength of 0.9 μm (Crump et al., 2007). Efficiency is 40% or higher in the wavelength range of 0.4 to 1.5 μm . The efficiency of VCSEL is slightly lower and reaches a maximum of 60% in the range of 0.8–1.1 μm (Kageyama et al., 2009). Liu PQ et al. (2010) have introduced a highly power-efficient quantum cascade laser. However, improvement in the overall efficiency of the laser is not so easy. As OWPT systems do not require a single longitudinal wavelength, single transverse mode, or high modulation frequency, it may be possible to improve efficiency in the future by further exploring suitable optical sources.

7.2 PV cell selection

The receiver element of any OWPT system must be intelligently developed to efficiently convert optical signals into electrical signals. The most traditional conversion techniques are thermoelectric, PV, and pyroelectric. Among these techniques, PV technology is known as the most mature, as it offers the highest efficiency to deliver high power over far distances. To achieve high performance, temperature, PV cell material, laser power, and wavelength must be kept into consideration. In addition, the photon energy is assumed to be equal to or more than the bandgap energy

Table 6 Eye safe lasers (Kaushal and Kaddoum, 2017)

Laser type	Wavelength	Output power	Application
Nd:YAG crystal	1.06 μm	Up to 1 kW	Laser detection and ranging (LADAR)
Nd:YAG	0.532 μm / 1.065 μm	Up to 1 kW	Atmospheric communication
Raman-shifted Nd:YAG	1.545 μm	>10 kW	Light detection and ranging (LIDAR)
Fiber laser	Variable	Dozens of kW	Weapon
Nd:YAG	1.06 μm	Dozens of W	Sensor
Vertical cavity surface emitting laser (VCSEL)	1.064 μm	Dozens of W	Illuminator

Table 7 Related standards for eye safety of laser products (Soltani et al., 2021)

Year and Reference	Standard	Remark
2012 (Petersen, 1997)	ANSI Z136.2	Safe operation of optical communication systems using LEDs or LDs, including free-space links, optical fiber links, or combination of both
2013 (ICNIRP, 2013)	ICNIRP	Maximum exposure level to laser beam radiation for wavelengths ranging from 180 nm to 1000 μm
2014 (Rockwell et al., 2015)	ANSI Z136.1	Safe operation of lasers
2014 (IEC, 2007)	IEC 60825-1	General laser safety
2019 (Gies, 2019)	IEC 60825-12	Free space optics (FSO) communications

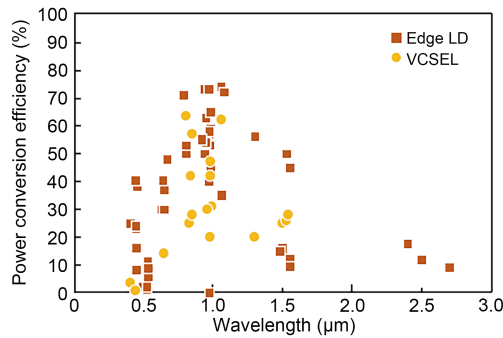


Fig. 26 Summary of the reported power conversion efficiency (PCE) of semiconductor lasers (edge LD and VCSEL) (Miyamoto, 2018)

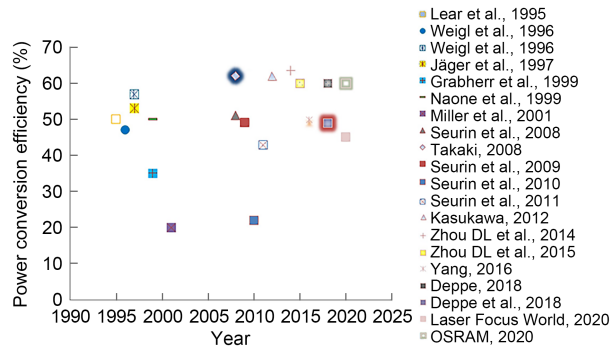


Fig. 27 Historical plot of the vertical cavity surface emitting laser (VCSEL) efficiency (Lear et al., 1995; Weigl et al., 1996; Jäger et al., 1997; Grabherr et al., 1999; Naone et al., 1999; Miller et al., 2001; Seurin et al., 2008, 2009, 2010, 2011; Takaki, 2008; Kasukawa, 2012; Zhou DL et al., 2014, 2015; Yang, 2016; Deppe, 2018; Deppe et al., 2018; Laser Focus World, 2020; OSRAM, 2020)

of the material for any PV cell receiver. This photon energy is proportional to its frequency. Thus, a monochromatic optical source with ideal frequency is taken as an ideal light source. The spectral response of different PV cells is shown in Fig. 28 (Mason, 2011).

It can be noticed from the graph results that the commonly available Si and GaAs PV cells provide the highest conversion efficiencies at 900 and 850 nm, respectively, while AlGaAs provides the highest response over 550–600 nm. Moreover, a PV cell offers an effective response for a given temperature with

generating more power if an intense light beam is incident on it (Höhn et al., 2016). Thus, we can conclude that PV cells efficiently work at high laser power intensity. In particular, GaAs (Matsuura et al., 2021) and Si (Putra et al., 2019) are commonly used, but it is also essential to choose the optical receiver according to the wavelength of the transmitter in order to improve the system's efficiency.

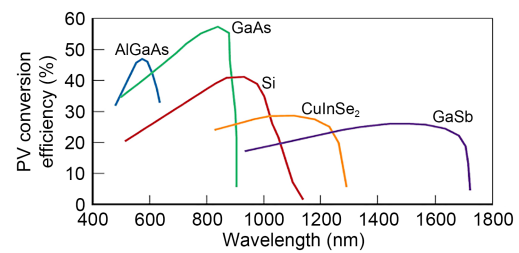


Fig. 28 Spectral response of photovoltaic (PV) materials (Mason, 2011)

Table 8 summarizes the efficiencies of various PV materials when they are illuminated by different laser sources. The GaAs PV cell has the highest efficiency around 850 nm wavelengths (Valdivia et al., 2015). A Si PV cell has the highest efficiency around 900–950 nm wavelengths, but this region faces severe atmospheric absorption (Mason, 2011). On the other hand, InGaP and InGaAs are ideal for DPSSLs as they show the highest efficiency at wavelengths greater than 1000 nm.

Miyamoto (2018) calculated the wavelength-dependent PCE of a solar cell (Fig. 29). He stated that the wavelength of the optical source can be altered according to the bandgap energy of the solar cell to minimize thermal loss in any OWPT system. It is clear from Fig. 29 that the bandgap energy varies according to the wavelength of the irradiated light. High efficiency can be achieved at high irradiation optical power density and with a short wavelength range. The thermal heating of the solar cell limits the irradiation power. Photodetectors can also be used at larger wavelengths, but their narrow bandgap

Table 8 Efficiencies of various PV materials (Valdivia et al., 2015)

PV material	GaAs	Si	InGaAs	InGaP	CIS
Laser wavelength (nm)	810	950	>1000	>1000	>1000
PV cell efficiency (%)	60	53.4	28	27.7	40.6
Laser intensity (kW/m ²)	110	430	110	10	2.37
				2.6	10

energy (E_g) puts a limitation on PCE. There have been few studies using short wavelengths of UV and blue light, as this range is not suitable for solar power systems. Thus, researchers should focus on designing specific OWPT systems (Fafard et al., 2016; Perales et al., 2016) and widegap solar cells for a better PCE.

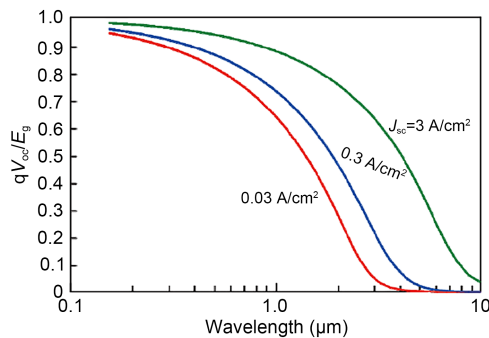


Fig. 29 Calculated power conversion efficiency (PCE) of a solar cell for various wavelengths and irradiation optical power (Miyamoto, 2018)

Fortunately, the high efficiency wavelength of an LD matches the E_g of the commercially available solar cells GaAs ($\lambda_g=0.88 \mu\text{m}$) and Si ($\lambda_g=1.1 \mu\text{m}$). Thus, the combination of these materials and corresponding wavelengths is practical. Table 9 summarizes OWPT efficiencies of current and future devices (Miyamoto, 2018). Currently, 10%–20% efficiency is possible through commercially available devices, while the best devices were reported to achieve almost 50% efficiency. These efficiencies are sufficient for systems which do not require higher efficiency for their operation. Moreover, 70% or higher efficiency is expected by improving the efficiencies of both the LD and solar cell. However, this performance requires a lot of effort by the research community in research on widegap optical sources and solar cells.

Recently, Ishikawa et al. (2020) from Tokyo City University, Japan evaluated the use of bromide-based perovskite flexible thin film solar cells to develop an

OWPT system. Bromide-based perovskite has a high bandgap of 2.3 eV, which makes it suitable for solar cell applications. The flexible thin film solar cells provide good performance under monochromatic light, with efficiency of more than 20%. High-efficiency perovskite silicon tandem solar cells (Todorov et al., 2014; Sahli et al., 2018) have also emerged as promising candidates for OWPT (Schubert et al., 2009) and IoT devices (Raifuku et al., 2016). The Shockley and Queisser theory shows that the open-circuit voltage (V_{oc}) of a solar cell is a linear function of the bandgap energy. Therefore, if E_g increases then the maximum voltage efficiency also increases. For OWPT applications, the CsPbBr₃ system offers some advantages, including thermal stability. In a recent research (Ishikawa et al., 2020), the MAPbBr₃ system has shown the best optical properties among wideband perovskite materials. An efficiency of 20.2% under blue LED has been achieved by high-quality MAPbBr₃. A research group from Tokyo City University is also working on OWPT applications of CsPbBr₃ (Murata et al., 2020).

Current, most solar cells are designed to capture sunlight. In such conditions, the surface of the solar cells appears to be black after absorbing light of various wavelengths. In OWPT applications, this property of solar cells becomes a potential obstacle. Typically, the solar surfaces are black, which restricts the visible appearance of OWPT devices.

In an OWPT system, the optical source is effective monochromatic light from a laser or LED, which is different from common sunlight. The wavelength of the optical source is chosen according to power transmission properties. At present, the IR range is considered optimal for mature GaAs and Si solar cells. Even though there are several restrictions and conditions, it is feasible to alter the appearance of a solar cell using color filters. Visible color filters can be applied to alter the common black appearance

Table 9 Efficiencies of various PV materials (Miyamoto, 2018)

Work plan	LD type	LD efficiency (%)	Solar cell type	Solar cell efficiency (%)	WPT efficiency (%)
Current	Common LD	35	Si-SC	30	10
	Common LD	35	GaAs-SC	50	17
	Best LD	74	Best GaAs-SC	66	49
Future	GaAs	85	Si	50	43
	GaAs	85	GaAs	75	64
	GaN	85	GaN	85	72

of a solar cell to enhance the visual appearance of consumer appliances, without compromising the efficiency of the solar cell.

Different kinds of filters are available, based on their absorption: sharp wavelength cut filter (SCF), visible dichroic filter (DIF), and visible dichroic mirror (DIM). The colors of the different filters are shown in Fig. 30.

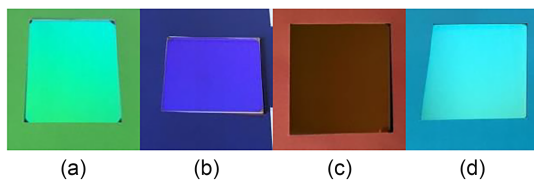


Fig. 30 Colors of DIF-MAG (a), DIF-YEL+SCF-52Y (b), DIM-GRE+SCF-52Y (c), and DIF-RED+SCF-52Y (d)
The center is a filter installed on black matter and the outside is the color of printed matter (Liu Y and Miyamoto, 2019b)

A research group from the Tokyo Institute of Technology, Japan applied frosted glass to alter the rough surface of a solar cell to obtain light scattering. They concluded that the typical appearance of OWPT can be altered with an acceptable low deterioration in performance. Although filters can change the color, they are not enough to control the overall appearance. Thus, Liu Y and Miyamoto (2019a) applied frosted glass to achieve light scattering, which can enhance the appearance characteristics. Anti-reflection coated devices can be applied to enhance the performance of OWPT systems in the future. In a previous study (Liu Y and Miyamoto, 2019b), a connected thin film GaAs solar cell was fabricated using a 3D printer. Fig. 31 shows two color filters, DIF-RED and DIM-GRE, with and without frosted glass. The module surface became smooth and the appearance was improved after adding frosted glass.

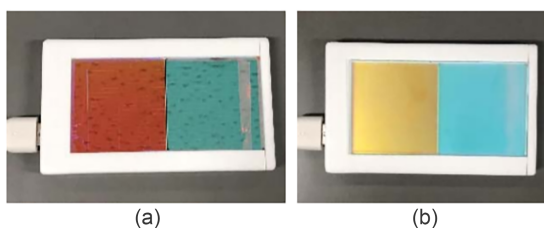


Fig. 31 OWPT light receiver module without (a) and with (b) frosted glass (Liu Y and Miyamoto, 2019a)

8 Challenges and counter measures in OWPT

This section highlights several critical challenges for OWPT. We briefly discuss challenges associated with efficiency, safety, communication, propagation losses, thermal effects, beam collimation, and the pointing issue. We also suggest some solutions to overcome these challenges.

8.1 Efficiency improvement

Improving the efficiency of any OWPT system is a challenging task. With the expanding advancements in OWPT, its use cases are increasing. The overall efficiency is not suitable for its commercial development as HILPB systems provide efficiency of only around 10%–20%, which is a great hurdle. The research fraternity is focusing on efficiency improvement for commercial deployment and researchers are working to improve PV cell efficiency. In 2003, the US Department of Defense (DoD), under the Defense Advanced Research Projects Agency (DARPA) Super High Efficiency Diode Sources (SHEDS) program, dedicated significant research and resources to improving the efficiency of LDs to 85%.

8.2 Safety

At present, laser technology is being implemented in hospitals, offices, and private enterprises. Therefore, it is critically essential to introduce a laser-safe environment. Inappropriate usage of laser devices can cause hazards, including irreparable injury to the skin and eyes. The biological hazard occurred by lasers is due to thermal, photochemical, and acoustical effects. Thus, it is important to design stringent safety solutions, like scanning light detection and ranging (LIDAR). Thus, precautionary steps must be taken to mitigate retinal damages. A possible solution is to consider larger wavelengths beyond this region. However, it incurs complacency, low efficiency, and high cost. It is imperative to design laser safety guidelines and regulations. This involves accurate control, effective hazard analysis, laser safety analysis, and knowledge of laser regulations (IEC, 2007). Effective hazard analysis includes many parameters, as discussed below.

8.2.1 Maximum permissible exposure and accessible emission limit

The MPE defines an accurate number for laser safety calculations: it is the lowest radiant exposure or irradiance that does not cause any biological damage to human eyes or skin. It is a function of exposure time and laser wavelength. It is the highest power in W/cm^2 that is non-hazardous for specific exposure conditions. MPE and exposure time variation for common laser wavelengths is shown in Fig. 32.

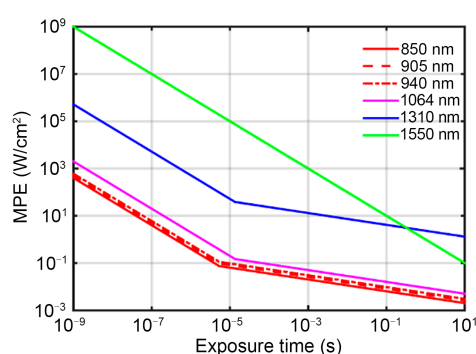


Fig. 32 Maximum permissible exposure (MPE) vs. exposure time (Sun et al., 2019)

Another crucial factor is the accessible emission limit (AEL), which refers to the maximum radiation power that can be emitted from a particular laser. It is used to classify lasers, but does not define system safety. The AEL value should be kept into account for the proper use of lasers. For instance, if we keep the power level below a certain threshold, any unintentional exposure to the laser beam will not cause any hazard.

8.2.2 Laser beam control measures

Direct beam exposure can be substantially reduced by accurate safety constraints built into the system. The presence of any object within the field-of-view of a laser is crucial. Sufficient time is required before any object appears into the proximity of the optical beam path. In these conditions, suitable engineering control mechanisms are needed that can accurately attenuate or terminate the optical beam. Beam control is also important, as the receiver can reflect some part of the incident optical power. The receiver part contains a gimbal sensing mechanism that can reduce the reflected energy to redirect it into

a safe dissipation area. Furthermore, mobile and end-to-end OWPT systems should be designed to overcome reflection and redirect this optical power into any absorber target, to avoid any damage.

8.2.3 Nominal ocular hazard distance

The nominal ocular hazard distance (NOHD) (de Luca et al., 2012) refers to the distance from the source where the MPE is equal to the radiation. Here, the energy at a distance smaller than the NOHD is equal to or lower than the MPE limit, while distances longer than the NOHD are called nominal hazard zones (NHZs). The value of NOHD is calculated using the ANSI Z136.1 standard, to find the safe regions near the laser. In addition, physical laser precautionary measurements should be taken into account. Eye wear is also specific for lasers. An important parameter of eye wear is the optical density (OD) of the lens, which is a function of the irradiance and power and affects the attenuation of energy passing through the eye wear lens. Correctly selected eye wear will attenuate the beam to a level below the MPE limit.

8.3 Optical communication

In the future, LPT technologies such as HILPB will integrate efficient optical communication. By using a PV cell as a receiver to ensure communication, data can be transferred along with power transfer, resulting in a dual-application system. A technique to integrate a communication link onto transmitted photon energy will introduce cutting-edge robust free space optical communication. However, it is still a crucial concern to integrate a communication link into an optical power link.

8.4 Propagation losses in the optical beam

Three factors of free space usually limit the performance of the optical system: (1) expansion of waves beyond the capability of the optics to collimate, (2) distortion of wave fronts because of variation in the refraction index of air, which is influenced by gradient caused by wind and temperature, and (3) dust and water particles, which scatter or absorb photons.

Absorption and scattering coefficients alter according to the sizes of airborne particles. In normal situations, absorption and scattering do not pose severe

effects such as those caused by atmospheric gradients and distance. Distance is a prominent parameter that causes severe impacts on beam transmission. The laser mode structure is the appropriate determinant of optical power over distance. In common cases, two different kinds of lasers are considered, single-mode and multi-mode. Single-mode lasers, e.g., disk laser, are used to transmit optical power up to 1 km distance. However, it is hard to reach the diffraction limit by multi-mode lasers. Therefore, both have certain limitations.

8.5 Thermal effects on system performance

As lasers perform better in colder conditions, it is essential to remove heat. The PCE is better in a cooling environment. Crump et al. (2006) demonstrated a PCE of 76% at 10 °C, and up to 85% at -50 °C for a 975 nm broad area LD. At ambient temperature, a heatsink arrangement can be a good choice. We need to be careful for specific lasers such as a C-Mount laser, which is not good at removing heat. Thermal heat also degrades the overall performance of the optical system. Lasers and PVs are different from silicon integrated circuits as they show sensitivity to heat. A 14XX InP laser loses efficiency at 1.1% per degree Celsius of heat, while a 12XX quantum dot laser loses efficiency at 0.6% per degree Celsius. Nowadays, these lasers are not available beyond 1400 nm wavelengths. Heat also reduces the PV voltage. So, it seems that a proper way to reduce thermal effects and sink heat from packages is the key objective. Fig. 33 shows the thermal effect on a multi-mode InGaAsP/InP 1400 nm edge-emitting LD.

Thermal degradation of PV cells is also important. Usually, limited power is available at the receiver site for a power beaming system. Thermal performance can be enhanced using efficient materials which operate near match points with a better interconnection. A fan can be incorporated as another suitable alternative.

8.6 Pointing

There should be accurate pointing between the transmitter and the receiver. For a 10-m distance, with a tolerance of +3 mm or -3 mm at the receiver, the system should point within 0.3 mrad. A good mechanical design is required to lock the device without

jostling it at this close tolerance. In addition, the threads of off-the-shelf machine nuts and screws lack proper consistency in some systems. It is suggested that the receiver should point at the transmitter depending upon the accurate optical arrangements.

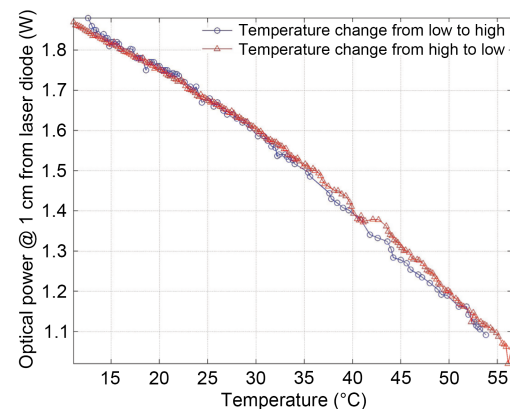


Fig. 33 Thermal derating of a multi-mode edge-emitting InGaAsP/InP LD (Sahai and Graham, 2011)

8.7 Collimation of multi-mode lasers

1. Fast axis collimation. Collimating a fast divergence beam is difficult. A relatively large amount of light is lost if a high-powered laser beam is 40° beyond the axis. An aspheric lens is a suitable option for the collimation of fast beams, as it can adjust the two axes differently.

2. Slow axis collimation. Collimation of a multi-mode laser is also complicated, as it has many horizontal modes. The beam size will vary with the distance. To ensure safe operation, it is required that the beam should not appear to a focus at any specific range, and thus adjusting this divergence is hard.

9 Conclusions

WPT technologies are still in their infancy, and require a deep research focus and wider investigations in the context of reliable consumer electronics and realistic mobile devices. Among WPT techniques, OWPT offers several advantages in terms of sending power in underwater environment and implantable devices inside human skin. It has the potential to transmit high intensity light over longer distances due to its small divergence angle and beam size. However, it requires an additional element for beam steering,

as the laser beam must be steered at the receiver. For IoT terminals such as beacons, tags, and sensors, physical wires and batteries are not effective due to their complexity, installation, and maintenance costs. OWPT is a promising alternative to traditional charging mechanisms with its potential features of small beam size, good directionality, and long-distance transmission.

In this study, the basic concepts of OWPT have been presented. In particular, the OWPT working principle, system design, potential features, and various OWPT projects for mainstream applications are discussed. We have also suggested that OWPT is an essential element to supply power to IoT terminals. We have highlighted the impacts of dynamic OWPT. Moreover, our study dealt with the rudimentary physics of OWPT technologies including optical beamforming, DLC, ADLC, SLIPT, HILPB, and T2T OWPT. We also shed some light on research efforts dedicated to these OWPT technologies. Besides introducing the OWPT theory, this survey provides a practical guideline for OWPT system design. We have given a comprehensive overview of OWPT technologies and basic principles, and the challenges involved in implementing OWPT technologies with regard to suitable laser and PV cell selection. We have discussed a range of open challenges and counter measures. We believe that this review will be helpful in integrating research and eliminating technical uncertainties, thereby promoting progress and innovation in the development of OWPT technologies.

Contributors

Syed Agha Hassnain MOHSAN drafted the paper. Haoze QIAN and Hussain AMJAD helped organize the paper. Syed Agha Hassnain MOHSAN and Haoze QIAN revised and finalized the paper.

Compliance with ethics guidelines

Syed Agha Hassnain MOHSAN, Haoze QIAN, and Hussain AMJAD declare that they have no conflict of interest.

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