400 mW class high output power from LED-array optical wireless power transmission system for compact IoT

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Abstract For internet-of-things (IoT) terminals, which consist of many sensors and beacons, wiring and using battery are ineffective power supply methods due to excessive installation and maintenance work cost. Nowadays, existing wireless power transmission technologies are still immature. In this paper, LED-array optical wireless power transmission (OWPT) systems which have a portable size and can supply electricity power of nearly 400 mW remotely at 1 m for compact IoT terminals are designed and demonstrated.

Keywords: OWPT, LED, lens system, semiconductor device

1. Introduction

In today’s information and digital societies, the IoT plays an indispensable role in the field of advanced wireless information communication [1]. In order to efficiently utilize the information acquired from IoT terminals, installing great number of sensors, beacons and tag terminals is critical. However, issues exist in supplying power to such a large number of terminals. The usual method is wiring or using batteries. On the other hand, laying work, laying space, and maintenance will be burden of wiring of a large number of terminals, and replacement and charging of the battery also needs excessive labor cost [2]. More importantly, since the power amount of the battery is limited, the operating time, and some functions of information processing and communication will be sacrificed with limited power [3].

Therefore, if recharging is expected in an easy way, the performance of various IoT terminals can be significantly enhanced, and almost terminal design concepts will be modified. Since IoT terminals in many applications are installed at the position that is difficult to reach by human, remote power supplying is necessary as a compact system. Therefore, wireless power transmission (WPT) [4] is believed to be a good candidate. Existing WPT technologies are almost based on electromagnetic induction or magnetic field resonance, and they need to approach closely less than a few 10 cm to terminals in order to transmit power [5]. For sharp beaming using microwave which can extend the transmission distance, complicated and large phased array antenna is required [6]. The use of these RF electromagnetic waves is limited in frequency regulation and concerning about noise interference with other equipment [7].

Thus, optical wireless power transmission (OWPT) technology is attractive [8]. In OWPT, light rays are carriers of power energy that can transmit long distances. Compared to other WPT technology, OWPT is usually small size and simple configuration, which is advantageous for movable capability. In addition, it can transmit power to long distance with small energy dissipation due to its high directivity feature [9]. There is no frequency regulation and no noise interference because of DC operation. With such merits, the OWPT system is very suitable for power feeding of IoT terminals which are installed in a variety of working requirements and environments. Figure 1 shows a schematic application of OWPT. Portable light sources can be carried by humans, robots, or drones. Fixed light sources with a direction movable function are also assumed. IoT terminals are charged sequentially by light irradiation.

Currently, almost researches of OWPT are laser-based [10], because it has advantages such as high power, high directionality, low divergence, and narrow spectrum. However, the disadvantages of lasers are also critical. Generally, all laser products are severely regulated [11] because of its possible hazard of eye damage as well as harm to equipment and usage environment. This means that laser-based OWPT systems are difficult to be an application integrated into daily life or used by human workers at current. Due to these reasons, research on the feasibility of light sources other than lasers is necessary. By considering the benefits such as low cost, low temperature sensitivity [12], recent improved efficiency and output power [13], small size, and sufficiently narrow spectrum for using in OWPT, a recent high-performance light-emitting diode (LED) is believed as an important candidate in the OWPT system. The initial discussion of the single LED OWPT system was reported prior [14]. A schematic illustration of the single LED OWPT

Fig. 1 Schematic illustration of portable OWPT system.
In this previous research, the highest output power achieved from a single LED OWPT system was around 224 mW, with an irradiation size of 2.1 cm × 2.3 cm and an output power of 1040 mW of an infrared (IR) LED with a peak wavelength of 810 nm [15]. A flexible GaAs solar cell with the size of 1.7 cm × 1.7 cm was used as the receiver. 1 m was chosen as the typical transmission distance. As a power supply system, one of the main targets of this research is to improve the final output power, and increasing the beam energy is a simple but effective solution. Unlike semiconductor lasers that can increase output power with a small output aperture [16], the power density of commercially available single-chip LED is typically limited at around 1 W/mm² [17]. The usual method to improve total intensity is increasing the size of the LED chips or arranging multiple chips compactly in one LED module [18]. However, such methods will increase the total emitting area, and eventually lead to multi times larger irradiation size [14]. This causes difficulty of increasing output power from limited receiver sizes.

In this paper, increased output power from the light receiver side is achieved by designing the LED-array OWPT system. Multiple LEDs with a well-designed optical (lens) system can be an effective and easy method to improve output power without significantly increasing the irradiation size. In section 2, analysis based on a simulation model of two kinds of the LED-array OWPT system configurations is discussed. In section 3, confirmation by the experimental performance of the LED-array OWPT system and data analysis is reported, and research results are summarized in the last section. A part of this LED-array OWPT system and simulation results were reported as the initial proposal of the system [19, 20, 21], however, in this paper, the detailed discussion and experimental confirmation are carried out.

2. Basic concept of LED-array OWPT configurations

A novel LED array method is applied in this research. Because of the spatial incoherence of LEDs [22], collimation on whole transmission distance is impossible, however approximate collimation in very short distances is not difficult. A collimation lens [23] is used after the LED, and it transfers light rays to be parallel. One Fresnel lens which is used as a thin and light weight system is applied to rearrange the intensity distribution and focus behind the collimation lens. With such a configuration, the level of compactness can be significantly increased and the vertical height of the system can be significantly reduced. In addition, since the rays are collimated, correct focusing can be achieved even Fresnel lens is closely placed after the collimation lens, which also allows the system horizontal length can be significantly compressed. In fact, the horizontal length of the system can be reduced around 60% with such an array configuration compared with the single LED OWPT system reported previously [24].

2.1 Single-set collimation lenses configuration (configuration A)

As shown in Fig. 3, one set of lenses is used to collimate and a Fresnel lens can be installed closely after the collimation lens. The name of this configuration is simplified as “configuration A” in this paper. The number of optical elements is small in this configuration, it can thus achieve very small irradiation size. On the other side, the light source needs to be placed at the back-focus point of the collimation lens in order to collimate accurately. In addition, the collimation lenses applied in OWPT system usually have a relatively large back focal length, thus geometrical loss of the collimation lenses will be large because the component of light that cannot be incident on the lens increases.

2.2 Double-set collimation lenses configuration (configuration B)

In order to solve the issue of low lens system efficiency in the LED-array OWPT, another configuration (configuration B) is proposed and shown in Fig. 4. In this configuration, the collimation is finished by two sets of lenses in two steps. The light source can be placed closely near the surface of the first collimation lens set, and the light rays can be collimated correctly by modifying the distance between the two sets of collimation lenses. By this configuration, the geometrical loss between the light source and the collimation lens is significantly reduced, and the lens system efficiency will be increased. On the other hand, the transversal magnification value [25] of the whole lens system will increase due to one more set of lenses is inserted into the lens system. Therefore, the irradiation size at the target distance will increase slightly.
but reduced efficiency, while configuration B has a slightly complicated configuration with a slightly larger irradiation size but high efficiency. Both configurations have their individual advantages and can be adopted to different applications and work environments.

### 2.3 Numerical analysis of basic characteristics of LED-array OWPT configurations

Figure 5 shows the simulation results of two kinds of array configurations with different numbers of LEDs and different sizes of the solar cell at a transmission distance of 1 m. The data of a single LED OWPT system that reported prior [14] is also included in order to compare. The transmission distance is determined mainly by the focal length of the Fresnel lens. Assumed LED chip is OSRAM, SFH-4703AS [17] with an active area of 0.75 mm $\times$ 0.75 mm, and this LED chip was used in the experiment of previous report. The light output power is 1040 mW and the typical divergence angle is $40^\circ$. This IR LED is almost the highest intensity and smallest active chip size one that available in the commercial market. The official simulation model of IR LED was used as the light source in the simulation. In the simulation, a collimation lens with both a 50 mm diameter and a focal length was modeled, and the Fresnel lens had a focal length of 1 m and an aperture diameter of 120 mm. Figure 6 shows the irradiance map of two configurations. The electrode pattern on the chip surface creates a non-square irradiation, and also influences the intensity homogeneity.

In the case of the 3 LEDs system with configuration B, it can achieve around 1800 mW maximally. Notice that the transversal magnification value is determined by the individual lens set of each light source, and thus the final irradiation size of both configuration A and B will not change no matter how many LEDs are applied. Therefore, the irradiation size of configuration B is always 3.8 cm $\times$ 4 cm. On the other side, the 4 LEDs OWPT with configuration A can achieve around 1600 mW intensity maximally, and the lower intensity is caused by its lower lens system efficiency that discussed above. However, saturated intensity can be obtained even from smaller solar cell (side length of 3 cm) by configuration A because of the small irradiation size. The 2 LEDs OWPT with configuration B and the 3 LEDs OWPT with configuration A can transmit approximately the same saturation intensity, which is 1400 mW, and the 2 LEDs with configuration A reaches similar amount of intensity with a single LED OWPT system as shown in Fig. 5.

According to simulation results, the average irradiance of the 4 LEDs array system with configuration B is higher than that of a single LED OWPT system. Therefore, appropriate design of the LED-array OWPT configuration is effective in increasing the output power. In addition, the result is effective for improvement of the photovoltaic (PV) conversion efficiency because the PV conversion efficiency is increased under high irradiance [26]. According to our previous report, the PV conversion efficiency of a single LED OWPT system was around 42%. Therefore, exceed 1 W output power of the 4 LEDs array system with configuration B is expectable.

### 3. Experiment of LED-array OWPT system

#### 3.1 2 and 3 LEDs array OWPT system (configuration A)

In this section, the experiment results of the 2 LEDs and 3 LEDs array OWPT system with configuration A is discussed. Figure 7 shows an example of a simulation model of the 2 LEDs array OWPT system with configuration A by optical design software of Zemax, and Fig. 8 shows the experimental setup of the 3 LEDs array OWPT system with configuration A. The configuration was optimized by using Zemax. Figure 9 shows IR images of irradiation at the solar cell distance. Since the irradiation shape is not regular rectangle, the irradiation size is defined as size of a rectangular area that can just cover the entire irradiation.

In the experiment of configuration A, the same LEDs as the simulation discussed in section 2 were used, and the
output power of each LED was 1040 mW. As for lens system, aspheric condenser lenses with a 50 mm aperture and a 50 mm focal length (SIGMAKOKI, AGL-50-50P) [27] were used as collimation lenses, and a Fresnel lens (NTKJ Co., Ltd., CF1000) [28] with 1 m focal length and 120 mm aperture diameter was used to transmit intensity to the solar cell. In this experiment, no anti-reflection coating was applied to lenses. A GaAs solar cell with a 34 mm x 50 mm size was installed as a receiver at a distance of 1 m. The simulation and experiment results are shown in Table I.

Table I Results of configuration A (2 and 3 LEDs array OWPT)

|                        | Sim. (2 LEDs) | Exp. (2 LEDs) | Sim. (3 LEDs) | Exp. (3 LEDs) |
|------------------------|---------------|---------------|---------------|---------------|
| Irradiation size (mm x mm) | 26 x 30       | 27 x 30       | 26 x 30       | 34 x 44       |
| Intensity on solar cell (mW) | 808           | 560           | 1189          | 850           |
| Lens system efficiency (%) | 38.9          | 26.9          | 38.1          | 27.2          |
| Output from solar cell (mW) | 196           | 316           |               |               |
| PV conversion efficiency (%) | 34.9          | 37.2          |               |               |

In all the experiments in this research, the intensity obtained at the target position or solar cell is measured by an intensity meter with a round shape detector with a diameter of 50 mm. Theoretically, the LED-array system with configuration A will have the same irradiation size and lens system efficiency no matter how many LEDs installed.

From Table I, the measured irradiation size of the 2 LEDs array system was very close to the simulation result. However, the irradiation size of the 3 LEDs array system in experiment was slightly larger than the simulation result. This difference is caused by alignment deviation in the experiment. With numbers of LEDs increasing, the requirement of accurately alignment is harder to achieve. Thus, obvious displacement of final irradiation occurs. The solar cell received intensity of the simulation is not agree with the experiment results. This can be explained by many uncertain elements in experiment such as increase of LED temperature [29] or the smaller effective aperture size of the applied lens. The lens system efficiency can be calculated out around 38% in simulation and 27% in experiment, and approximately 45% total intensity lost between the LED array and the collimation lenses. The output of the 2 LEDs array system measured from the solar cell was 196 mW, and 316 mW of the 3 LEDs array system. Compared with the previous experimental results of the single LED OWPT system, the output of the 2 LEDs array OWPT system is even lower. A part of the performance degradation is caused by irradiance reduction due to lens loss and larger irradiation.

The output of the 3 LEDs array OWPT system is increased to about 1.5 times higher than the previous single LED OWPT system, and it means that the efficiency is deteriorated to about half. Essentially, irradiance reduction leads to lower PV conversion efficiency. However, as the PV conversion efficiency value shows in Table I, with the number of LEDs increased, the irradiance on the surface of the solar cell strengthened, thus the PV conversion efficiency increased from 34.9% of the 2 LEDs array system to 37.2% of the 3 LEDs array system, and the PV conversion efficiency of the 3 LEDs array OWPT with configuration A already close to 42% of the single LED OWPT system that reported prior. Therefore, the LED-array OWPT with configuration A can still provide a high output if the number of LEDs is large enough.

3.2 2 and 3 LEDs array OWPT system (configuration B)
In this section, the experimental results of the 2 LEDs and 3 LEDs array OWPT system with configuration B are shown.

The experimental setups of the 2 LEDs and 3 LEDs array OWPT system (configuration B) are shown in Fig. 10 and Fig. 11, respectively. As for the 2 LEDs array system, the two IR LEDs were arrayed side by side, the distance between the two LEDs was 50 mm. In the 3 LEDs array system, the 3 LEDs were arrayed as equilateral triangle pattern with 50 mm side length. Two sets of collimation lenses applied to the system. The first set was closely installed after the LED array, and the second set was placed with a certain distance from the first set, then a Fresnel lens was installed tightly behind. The elements applied in this and all other experiments in this paper have the same parameters that were stated in section 3.1. Figure 12 shows IR images of the
irradiations. Both the simulation and experiment results are shown in Table II for comparison.

Similarly, the 3 LEDs array system of configuration B shows different size irradiation in experiment and simulation, which is caused by alignment deviation. In configuration A, every 1 mm alignment deviation on one of the collimation lenses causes 20 mm irradiation displacement at 1 m distance, and such displacement becomes larger in configuration B. Thus, the irradiation size is larger in experiment unless lenses are exactly aligned. Comparing with configuration A, the lens system efficiency of configuration B increased to around 37%. Around 25% of total intensity lost between the two sets of collimation lenses. By applying collimation lenses with a shorter focal length, the distance between the two sets of collimation lenses can be shorten and the lens system efficiency can be increased. Conversely, the irradiation size will increase and a part of system performance will be sacrificed.

As discussed in section 2.2, the irradiation size of configuration B will slightly increase comparing with that of configuration A. Considering that one of the sides of the solar cell is shorter than the irradiation area that shown in Fig. 12 in the experiment, the accurate amount of intensity that received by the solar cell is difficult to measured and troublesome of the PV conversion efficiency calculation. Therefore, PV conversion efficiency is omitted in Table II. The final output measured from the solar cell is 268 mW for 2 LEDs array system and 380 mW for 3 LEDs array system, which is the highest record that achieved in the portable LED-based OWPT ever. Regarding the lens system efficiency shown in Table II, the value of the 3 LEDs array system is only 30.8%, which is much lower than the 2 LEDs array system, and this is unreasonable. The reason can be considered as part of intensity cannot be measured correctly by the intensity meter because the intensity meter has a detector that is smaller than the irradiation size of the 3 LEDs array system in this experiment. By estimation based on data from Tables I and II, the accurate intensity at the target position should be around 1080 mW, and the lens system efficiency can be calculated as 35.2% based on this value. The estimated value is shown in brackets of Table II.

Although, the PV conversion efficiency of configuration B is not shown, it should be slightly lower than configuration A. According to the experimental results, configuration B can achieve higher output power than configuration A when the number of LEDs is small. In spite of the larger irradiation area and lower PV conversion efficiency of configuration B, more intensity can be transmitted to the designed position with high-efficiency lens system. The output power difference of two configurations will decline or even reverse with number of LEDs increases. However, if the number of LEDs keep increasing, PV conversion efficiency of both configurations reached the theoretical limitation value [30], then configuration B still has advantage on output power amount. Another point is because the beam size of configuration B is larger, thus in the process of reaching the target distance from the transmitting side, the changing of beam size is more smoothly than configuration A, thus allows configuration B to be more tolerant of the transmission distance. As the result, configuration A can receive more than 50% intensity in the range of 450 mm – 1420 mm, while configuration B can achieve such result in the range of 250 mm – 1450 mm.

4. Conclusion

The feasibility of an optimized portable LED-array OWPT system for compact IoT terminals is proved in this paper. Two kinds of the LED-array configurations are discussed and compared. Particularly, 380 mW electrical power which is the highest record that been achieved with LED-based OWPT system has been measured from a GaAs solar cell with a 34 mm × 50 mm size at 1 m distance transmission in experiment. With the number of LEDs increasing, above 1 W output power by a portable LED-array OWPT system is expectable. The proposed system can be used for charging and power feeding of various IoT terminals.

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