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Transfer Efficiency of Underwater Optical Wireless Power Transmission Depending on the Operating Wavelength

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Optical wireless power transmission (OWPT) is a good candidate for long-distance underwater wireless power transmission. In this work we investigate the transmission efficiency of underwater OWPT, depending on the operating wavelength. We consider four operating wavelengths: infrared, red, green, and blue. We also consider the cases of pure water and sea water for the working conditions. Our results show that it is necessary to select the operating wavelength of underwater OWPT according to the transmission distance and water type of the target application.

Keywords : Optical wireless power transfer, Optical wireless power transmission, Underwater wireless power transmission
OCIS codes : (260.2160) Energy transfer; (350.4600) Optical engineering

I. INTRODUCTION

Wireless power transmission (WPT) has been commercialized in several applications, thanks to its convenience and flexibility [1]. Although many WPT technologies have been proposed and developed [2-7], current WPT technologies have several disadvantages, such as short transmission distance and causing electromagnetic interference (EMI) in other devices. Recently, optical wireless power transfer (OWPT) has been proposed to expand the effective transmission distance [1, 8-14].

OWPT can be a good candidate for long-distance WPT. OWPT is a WPT technology that uses light as the means of power delivery. In OWPT, a light source such as a laser diode (LD) is used at the transmitter to convert conventional electric power to optical power, and an optical-power receiver such as a photovoltaic (PV) cell or photodiode (PD) is used at the receiver to convert the received optical power to electric power. (If the original source power is optical power or the needed power at the receiver site is optical power, then power conversion may not be needed.)

Attenuation of OWPT is less than that for radio-frequency (RF) power transmission in free space. Thus it can deliver power over a longer distance. In addition, it does not cause EMI in other devices. Although it is expected that the transfer efficiency of the OWPT is lower than for other technologies over short distances, due to the need for power conversion (from electric power to optical power and vice versa), it will be higher than for other technologies over long distances, thanks to its low attenuation.

In this work we investigate the possibility to utilize OWPT for underwater WPT. Charging underwater robots is a hot issue in maritime engineering these days. However, RF-based WPT is not efficient in water, where the attenuation of RF waves is severe. OWPT can be a good solution for long-distance underwater WPT because attenuation of visible light is low in water. Although several works have investigated the underwater channel in underwater optical wireless communication [15, 16], they investigated only the attenuation coefficient of water and did not consider the electric-to-optic (E/O) conversion efficiency of a light source, nor the optic-to-electric (O/E) conversion efficiency of an optical receiver, because these are not the main issues in communication.

Recently our research team reported an experimental demonstration of underwater OWPT [8], but we did not

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investigate the dependence on operating wavelength in that previous report. Therefore, in this work we analyze the dependence on operating wavelength in underwater conditions, and discover the optimal operating wavelength for underwater OWPT. First, we investigate the back-to-back transmission efficiency of OWPT with different operating wavelengths, by investigating the E/O conversion efficiencies of light sources and the O/E conversion efficiencies of optical receivers. Second, we analyze the transmission characteristics of the underwater OWPT depending on different operating wavelengths in pure water, pure sea water, and normal sea water. In our analysis, we use the previous results of other studies on the attenuation coefficients of water. Finally, we determine the optimal operating wavelength of OWPT for different application situations.

II. BACK-TO-BACK TRANSMISSION EFFICIENCY

Figure 1 shows the block diagram and photograph of our experimental setup. At the transmitter, a LD can be used to convert electric power into optical power. At the receiver, an optical-power receiver such as a PD or a PV cell can be used to convert the received optical power into electric power. Between the optical-power transmitter and optical-power receiver, an optional beam collector such as a lens can be used to focus the optical beam on the surface of the optical-power receiver.

Assuming the E/O power conversion ratio of the LD is $C_{E/O}$ and the O/E power conversion ratio of the optical power receiver is $C_{O/E}$, the dc-to-dc transfer efficiency of the back-to-back OWPT, E_{BtoB}, can be expressed as [8]

$$E_{BtoB} = C_{E/O} \cdot C_{O/E}\,. \quad (1)$$

In the experiment, we use LDs with different wavelengths of 405 nm (blue), 531 nm (green), 660 nm (red), and 808 nm (infrared). The LDs were manufactured by LS Korea. Figure 2 shows the E/O conversion efficiencies and optical output powers as functions of the operating voltage of the LDs. The maximum E/O conversion efficiencies of the 405-nm, 531-nm, 660-nm, and 808-nm LD were 14.3%,

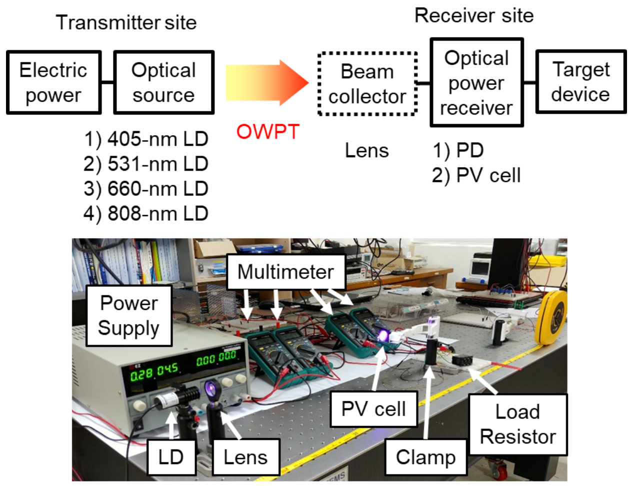

FIG. 1. Block diagram and photograph of the experimental setup.

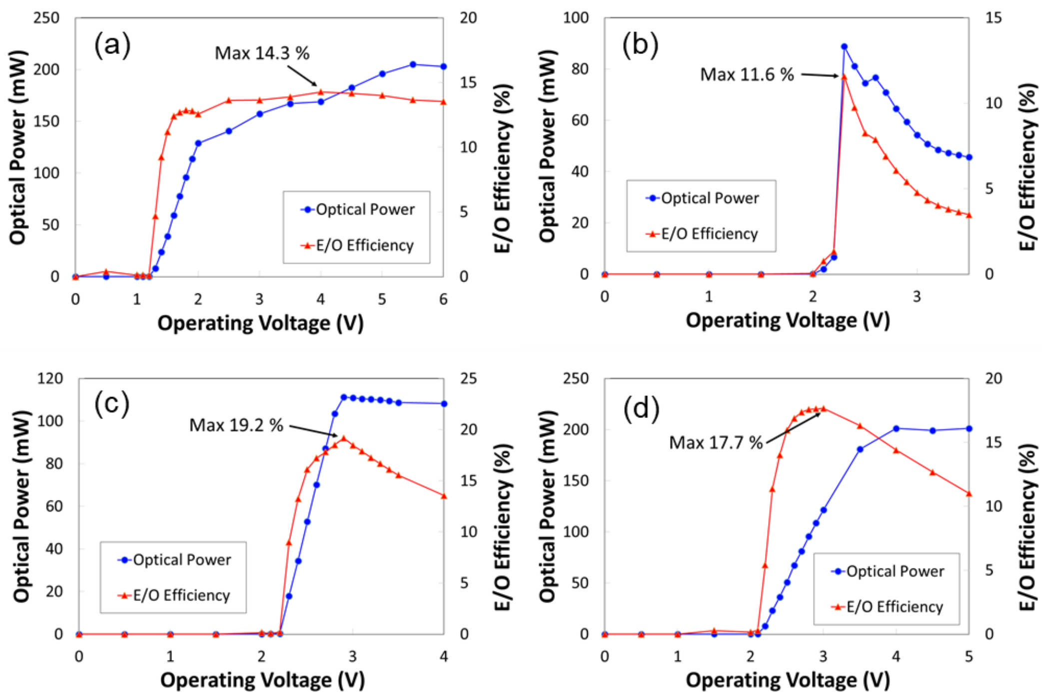

FIG. 2. Optical output power and E/O conversion efficiency of the (a) 405-nm LD, (b) 531-nm LD, (c) 660-nm LD, and (d) 808-nm LD.

11.6%, 19.2%, and 17.7% respectively, with optimization of the operating voltages. The maximum E/O conversion efficiency, the optical output power, and other operating parameters are summarized in Table 1.

Using these LDs, we investigate the O/E conversion efficiencies of a PV cell and a PD. A silicon PV cell (2.3 cm × 2.5 cm in size) and a Vishay BPV10 PD were used in the experiment. The PD is a silicon PIN PD with a diameter of 5 mm, a sensitive area of 0.78 mm^2, and a sensing spectral range of 380-1100 nm. According to the technical datasheet, the quantum efficiencies of the PD are about 12%, 32%, 47%, and 65% at the wavelengths of 405 nm, 531 nm, 660 nm, and 808 nm respectively.

TABLE 1. Operating parameters of the LDs at maximum E/O conversion efficiency

Operating parameters	Type of LD			
	405 nm (blue)	531 nm (green)	660 nm (red)	808 nm (infrared)
Electric voltage (V)	4.0	2.3	2.9	3.0
Electric current (mA)	296	334	200	229
Electric power (mW)	1184	768	581	688
Output optical power (mW)	169	88.8	111	121
Max. E/O conversion efficiency, $C_{E/O}$ (%)	14.3	11.6	19.2	17.7

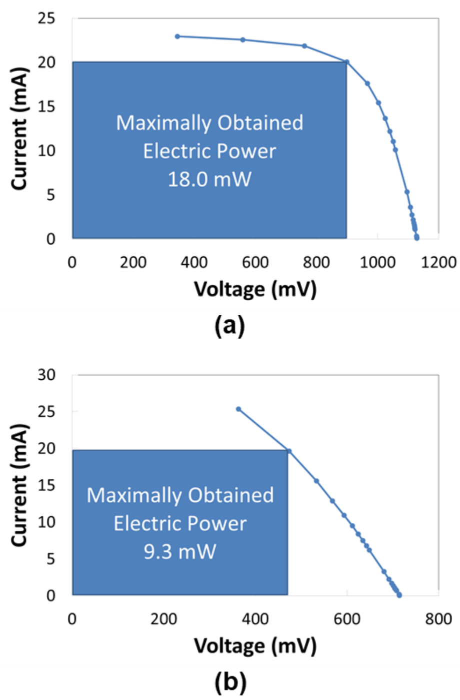

FIG. 3. Voltage-current plot for (a) the PV cell and (b) the PD by changing the load resistance, when the 660-nm LD is used as the optical power transmitter, operating at maximum E/O conversion.

Figure 3 shows the process of measuring the O/E conversion efficiencies of the PV cell and PD when the 660-nm LD is used as the optical power transmitter. In Fig. 3 we measure voltage and current of (a) the PV cell and (b) the PD while changing the load resistance, when the 660-nm LD is operating at maximum E/O conversion efficiency (*i.e.* the optical power is 111 mW). Then the electric power converted from the received optical power can be calculated by multiplication of the voltage and current. This implies that we can obtain the maximum electric power by optimizing the load resistance.

When the PV cell is used as the optical power receiver, as shown in Fig. 3(a), the obtained maximum electric power is 18.0 mW at a load resistance of 40 Ω. The optical power is 111 mW, and therefore the corresponding O/E conversion efficiency of the PV cell is 16.2%. Using a

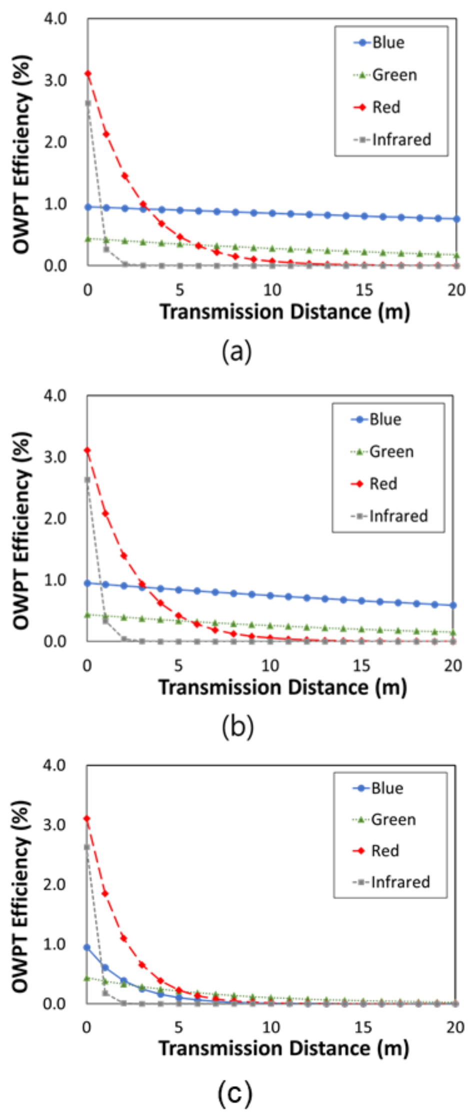

FIG. 4. OWPT efficiency as a function of transmission distance, in (a) pure water, (b) pure sea water, and (c) normal sea water.

TABLE 2. Back-to-Back OWPT efficiency

Optical power transmitter	$C_{E/O}$ (%)	Optical power receiver	$C_{O/E}$ (%)	E_{BtoB} (%)
405-nm LD	14.3	PV cell	6.7	1.0
		PD	4.6	0.7
531-nm LD	11.6	PV cell	3.8	0.4
		PD	1.5	0.2
660-nm LD	19.2	PV cell	16.2	3.1
		PD	8.4	1.6
808-nm LD	17.7	PV cell	14.9	2.6
		PD	7.8	1.4

similar process, we measure the O/E conversion efficiency of the PD shown in Fig. 3(b) as 8.4%. Although we only show the results for the 660-nm LD in Fig. 4, we perform the same process for the other cases (*i.e.* 405-nm, 531-nm, and 808-nm LDs) and obtain their O/E conversion efficiencies. Then, we finally calculate the back-to-back transmission efficiency in the 8 OWPT cases (4 LD cases × 2 optical-power-receiver cases) using Eq. (1). The results are summarized in Table 2.

In Table 2, the O/E conversion efficiencies using the PD are lower than those using the PV cell. The sensitive area of the PD is small (0.78 mm^2), and the epoxy lens of the PD is also small and imperfect, so there is some light leakage from the PD (although we do our best). Therefore, the received light cannot be fully focused on the sensitive area of the PD; this may reduce the O/E conversion efficiency. Because the PD was not originally designed as a power receiver in free space, the power-coupling issue and small sensitivity area yield worse performance than that of the PV cell. The PV cell has a much larger sensitive area, and power coupling is much easier than for the PD.

From Table 2, we can recognize that the back-to-back OWPT efficiency when using a PV cell is better than that when using a PD. Those better values of back-to-back OWPT efficiency are 1.0%, 0.4%, 3.1%, and 2.6% for the operating wavelengths of 405 nm, 531 nm, 660 nm, and 808 nm respectively. Therefore, we can conclude that the maximum OWPT efficiency is 3.1% with the 660-nm LD and a PV cell.

III. CHARACTERISTICS OF UNDERWATER OWPT

The main difference between free-space OWPT and underwater OWPT is the attenuation parameter of the medium. When the input power is P_0 and the attenuation coefficient is α, the transferred power P at the transmission distance L is given by

TABLE 3. Attenuation coefficients of pure water, pure sea water, and normal sea water

Wavelength (nm)	Attenuation coefficient (1/m)		
	Pure water	Pure sea water	Normal sea water
405	0.0113	0.0239	0.443
531	0.0454	0.0529	0.143
660	0.3798	0.4008	0.52
808	2.2935	2.0704	2.686

$$P = P_0 \cdot \exp(-\alpha L). \tag{2}$$

We consider that the attenuation coefficient of water is the sum of its absorption and scattering coefficients. The attenuation coefficient of pure water is well known [17], but the attenuation coefficient of sea water is not well known, because it depends on salt concentration, colored dissolved organic matter, plankton, detritus, etc. [15]. The most reliable data for the attenuation coefficient of sea water that we found came from a book and a paper [16, 18]. Table 3 shows the attenuation coefficients used in this study for the wavelengths of the four LDs. As shown in Table 3, the attenuation coefficient for infrared light is the worst in all three cases, and that for blue light is the lowest in pure water and pure sea water. However, in normal sea water the attenuation of green light is the lowest.

Using Eq. (2) and the attenuation coefficients in Table 3, we can obtain the underwater OWPT efficiency as a function of transmission distance. Figure 4 shows the OWPT efficiency as a function of transmission distance in pure water [17], pure sea water [16], and normal sea water [18]. In Figs. 4(a) and 4(b), the underwater OWPT efficiency for the red LD is the best within a transmission distance of 3 m, whereas it is the best within 5 m in Fig. 4(c). As shown in Table 2, the E/O conversion ratio of the red LD is the best, and the O/E conversion ratio of red light is the best in the PV cell. This leads to the best performance of red light in terms of back-to-back OWPT efficiency at short distances in water. However, the attenuation coefficient of red light is worse than those of blue and green light, so the OWPT efficiencies of blue and green light become better after several meters of transmission distance.

For example, the OWPT efficiency with the blue LD is best after 3 m, because the attenuation coefficient of blue light is lowest in pure water and pure sea water. The OWPT efficiency with the green LD is best after 5 m in the case of normal sea water, because the attenuation coefficient of green light is lowest and that of blue light becomes severe in normal sea water. Our results show that it is necessary to select the operating wavelength of underwater OWPT according to the transmission distance and water type of the target application.

IV. CONCLUSION

In this work we investigated the transmission efficiency of underwater OWPT at different operating wavelengths. Our results show that the best operating wavelength for underwater OWPT depends on the transmission distance and water type. This is because the back-to-back OWPT efficiency and attenuation coefficient of water both depend on the operating wavelength. Therefore, the operating wavelength of underwater OWPT ought to be selected according to the transmission distance and water type of the target application.

For example, our results show that red light is best over short distances within 3 m in pure water and pure sea water, and within 5 m in normal sea water. Meanwhile, blue light is best at longer distances over 3 m in pure water and pure sea water, whereas green light is best at long distances over 5 m in normal sea water. The main reason why the suitable color for long distances in normal sea water is not blue but green is that the attenuation of green light is lowest in normal sea water. This also causes the difference in the useful range of red light (3 m in pure water and pure sea water, and 5 m in normal sea water).

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