Paper

Highly Efficient Optical Powering System Using Feedback Control

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An optical powering system has been constructed, which shows high efficiency compared to conventional systems, almost independently of the power consumption of the load equipment. This is achieved by using feedback to control the optical power supply to meet the load requirements when the power consumption changes. The maximum system efficiency is 9% and the system can deliver 300 mW of electricity to a device at 200 m. The system mainly consists of a laser diode, optical fiber, photovoltaic cell, and electric double-layer capacitor, as an optical power source, transmission cable, optical-electrical power converter, and electrical energy storage device, respectively. This system is particularly useful for driving remote electrical equipment that requires complete electrical isolation and/or immunity from electromagnetic noise and also has variable power consumption.

Key words: Optical powering, Energy transmission, Photovoltaic cell

1. Introduction

Remote electrical equipment used for applications requiring complete electrical isolation, such as a lightning detector and an equipment for EMC (electro magnetic compatibility) evaluation, can be powered by optical power transmission[1][2]. For example, an optical powering system, consisting of a laser diode (LD), optical fiber, and photovoltaic (PV) cell, has been developed that can deliver approximately 300 mW of electricity to a remote device at a distance of 100 m[3]~[5]. In the system, the LD converts electrical power into optical power and sends it via the optical fiber to the PV cell, the cell converts the optical power back into electrical power, and the power output is supplied to equipment. The system has merits of complete electrical isolation and immunity from electromagnetic noise, since it has no electrical connection between the main power unit and the remote unit. Therefore, this sort of system is ideal for applications of powering to remote sensors, transducers, and instrumentations in bad environments. It also has the possibility of supplying up to around several watts of electricity.

However, if a constant level of optical power is supplied continuously, as in conventional systems, the total efficiency of the system (η) depends on the power consumed by the load equipment (P_c) when P_c changes. The η decreases as P_c decreases, because excess power is wasted at the PV cell in conventional systems. For this reason, average η decreases, if P_c varies. Actually, these days most types of electrical equipment show variable power consumption due to their multi functions.

Accordingly, we have constructed an optical powering system whose efficiency is independent of P_c. This is achieved by using feedback to control the optical power supply to meet the load requirements when P_c changes. In this paper, we report on the construction, characteristics, performance, and efficiency of the new system.

2. System Configuration

Our optical powering system consists of an LD, optical fiber, a PV cell, an electric double-layer capacitor (EDLC), a light-emitting diode (LED), and a power controller, as shown in Fig. 1. The LD converts electrical power into optical power and sends it via the optical fiber to the PV cell in the remote unit. The PV cell converts the optical power beck into electrical power, and the power output is used not only to drive the load equipment but also to charge the EDLC, which is connected in parallel. The LED emits light at an intensity proportional to the EDLC voltage, when it is above the threshold voltage (Vth). This LED light signal is sent back via another fiber to the power controller in the main unit, which uses it to control the optical power

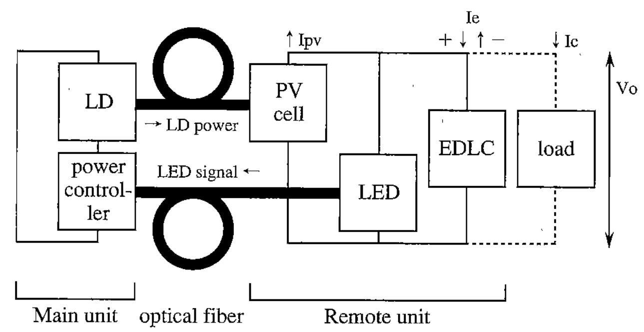

Fig. 1. System configuration.

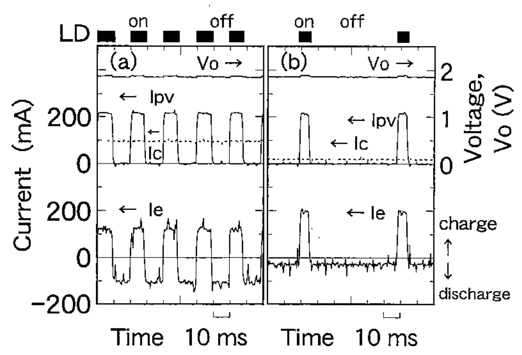

Fig. 2. I_{pv}, I_c, I_e, and V_o over time for R of (a) 20 and (b) 100 Ω.

Table 1. Specifications of optical powering system.

Component	Specifications
Laser diode	AlGaAs, 1.1 W, 810 nm
Optical fiber	Core: pure quartz, 200 μm φ
	Type: step index, NA: 0.2, 200 m long
PV cell	GaAs, 2 V, 3 mm φ
EDLC	2 F, ESR: 30 mΩ
LED	GaP, Vth: 1.7 V

supply (switching it on and off) of the LD, to maintain the EDLC voltage level constant needed by the load. Here, an intermittent modulation is used to control the LD output power, because conversion efficiency of the LD by this method is higher than when amplitude modulation is used.

The specifications of the optical powering system we used for testing are shown in Table 1. An AlGaAs LD with a 1.1 W output and 810 mm wavelength, integrated with a driver, was used as an optical power source (photonic power systems Inc., PPS-700-03). Step-index type 200 m long optical fibers, with a pure quartz core of 200 μmφ in diameter and a 0.2 numerical aperture (NA), were used as power transmission cables (Fujikura, S-200/250). A GaAs PV cell with a 2V output and 3 mmφ in diameter was used as an optical-electrical power converter. The PV cell was mounted with heat-conductive epoxy and wirebonded on a TO-8 header, and packaged in an FC-connected receptacle (photonic power systems Inc., PPC-2 SH-FC). The LD and PV cells were coupled with the optical fiber by an FC-type optical connecter. A pair of EDLC (1 F, 60 mΩ equivalent series resistance (ESR)), using conducting plastic collectors and activated carbon/carbon composite as polarizable electrodes, was used as an electrical power storage device (NEC, sample products, L-S-23-26)[(6)]. A 670 nm wavelength GaP-based LED with 1.7 V of Vth is used as a monitor of the EDLC voltage.

3. Experimental Results and Discussion

3.1 System Operation

We measured how the PV-cell output current (I_{pv}), the current consumed by the load (I_c), the EDLC current (I_e), and the EDLC voltage (V_o) varied over time for different loads. For the load, we used resistances (R) of 10 to 500 Ω. The results for R=20 Ω (P_c: 171 mW) and 100 Ω (P_c: 34 mW) are shown in Figs. 2(a) and (b), respectively. In both cases, V_o remained almost constant at approximately 1.85 V (<±1%), because the optical power supply of the LD was feedback controlled by intermittent modulation (switching it on and off) to maintain a V_o between approximately 1.84 to 1.87 V, which was monitored by the LED intensity. I_c also remained constant at a level depending on R. The PV cell generated current only when the LD supplied optical power. When I_c was less than I_{pv}, the excess supplied current was stored in the EDLC. When optical power was not supplied, in other words $I_{pv}=0$, the EDLC provided current by discharging. The relationship between I_{pv}, I_c, and I_e is almost $I_{pv}-I_c=I_e$. When I_c was lower than maximum I_{pv}, as shown in Fig. 2, the LD supplied optical power intermittently and the period of time that the LD was "on" was approximately several to 10 ms. The duty ratio of the LD changed when R varied, because the dropping rate of V_o depends on the value of P_c. When R increased, the duty ratio of the optical power supply decreased because the voltage dropped more slowly as the current from the discharging EDLC decreased. Thus, optical power transmitted from the main unit to the remote unit was saved when P_c decreased.

Fig. 3, shows the dependences of I_{pv}, I_c, I_e, and V_o on time when R changes frequently between 20 and 100 Ω, at 10 kHz. The V_o remains almost constant and the I_c changes between two levels depending on the value of R. The PV cell generates current only when the optical

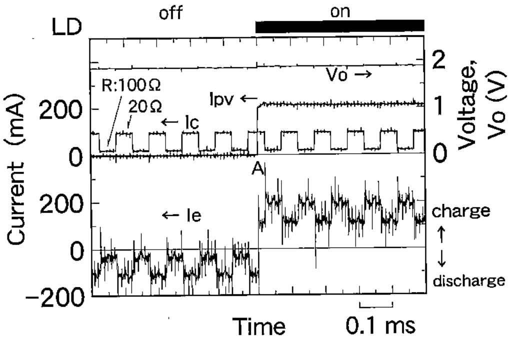

Fig. 3. I_{pv}, I_c, I_e, and V_o over time for changing R frequently between 20 and 100 Ω at 10 kHz.

power is supplied, after point "A" in Fig. 3, and before that point, the EDLC works as an auxiliary power source similar to the above description. The rise time and fall times of I_c are less than 1 μs, when P_c varies. Accordingly, our optical powering system can stably supply the power required by the load equipment even though P_c varies.

Furthermore, our optical powering system can also be used for load equipment whose P_c periodically exceeds the power output by the PV cell (P_{pv})[7]. In this case, auxiliary power is obtained by discharging the EDLC, when P_c is more than P_{pv}. Thus, our system can also stably supply the power to the load equipment as long as the mean value of P_c does not exceed P_{pv}.

3.2 Consumption Power and Efficiency of Each Component

(1) Laser Diode

The dependences of the consumed electrical power to drive the LD (P_{LD}), the ratio of P_{LD} between conventional and new systems, and P_c on R are shown in Fig. 4. The P_{LD} decreased significantly with increasing R due to decrement of the duty ratio, and was almost proportional to P_c in our system, whereas it was constant at approximately 4.2 W (current: 2.1 A, voltage: 2 V) in a conventional system. The P_{LD} was smaller in our system than that in a conventional system, and above $R=150$ Ω, in particular, it was more than one order of magnitude smaller. Thus, electrical power consumed at the main unit was saved significantly in our system when P_c decreased.

The LD output power was enhanced under the pulse driven condition, and the electrical-optical conversion efficiency was approximately 28%, whereas that was 23% under the CW driven condition. Because, the thermal release condition of the LD is probably improved in the pulse driven situation.

(2) Optical Fiber

The power loss of the optical fiber depends on fiber length, and the specific value of the fiber used in this study is 3.45 dB/km. Fig. 5, shows the relationship between transmission efficiency and distance. The transmitted power decreased exponentially with increasing fiber length. We used 200 m length optical fibers in this study, and after transmission of 200 m distance, the irradiation optical power to the PV cell was approximately 71% of the LD output power. This power loss includes coupling loss at the LD module and the optical fiber, and reflecting loss at the fiber end.

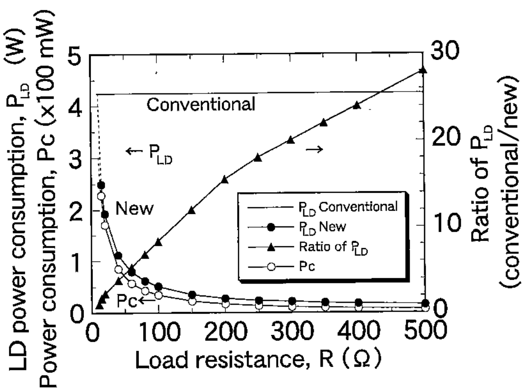

Fig. 4. Dependences of ratio of P_{LD} between conventional and new systems, P_{LD} and P_c on R.

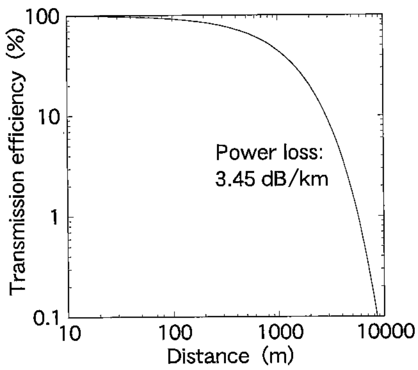

Fig. 5. Transmission efficiency vs distance of optical fiber.

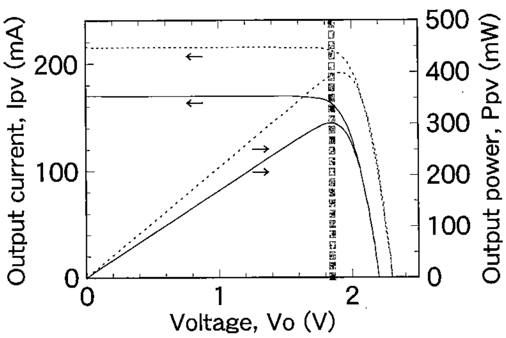

Fig. 6. Current-voltage and output power-voltage characteristics of PV cell (solid lines: CW driven mode, broken lines: pulse driven mode).

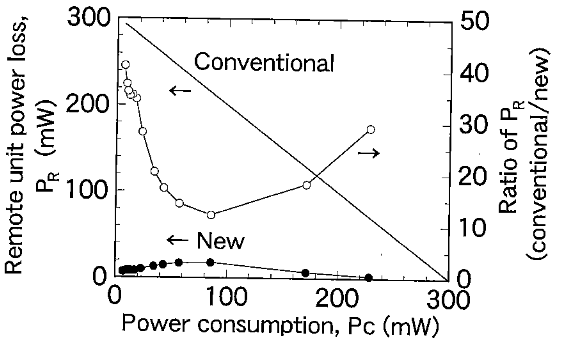

Fig. 7. Dependences of ratio of P_R between conventional and new systems and P_R on P_c.

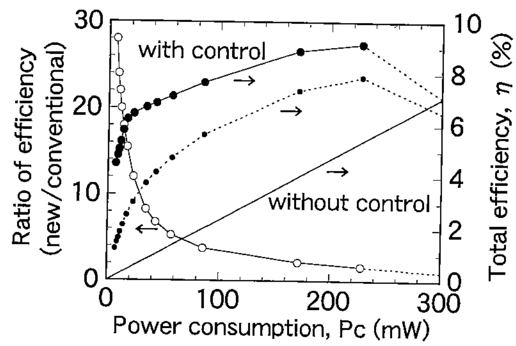

Fig. 8. Dependences of ratio of η between new and conventional systems and η on P_c. Broken line indicates η including consumption power of power controller circuit.

(3) Photovoltaic Cell

The current-voltage and output power-voltage characteristics of the PV cell are shown in Fig. 6. The PV cell operated at a constant 1.85 V in this study, which corresponds to the point of maximum output power and conversion efficiency, as shown in Fig. 6, even though the voltage can be set arbitrarily. The broken lines in Fig. 6, indicate the characteristics of the PV cell when the LD is driven in pulse (duty =1/2), and they are higher than those when the LD is driven in CW. In this case, irradiation optical power to the PV cell and conversion efficiency of the PV cell were 850 mW and 46% under the pulse driven condition, and 695 mW and 43% under the CW driven condition, respectively. The optical-electrical conversion efficiency of the PV cell is improved in the pulse driven situation, because the thermal release condition of the cell is also considered to be better.

(4) Others

The dependences of power loss at the remote unit (P_R) and the ratio of P_R between conventional and our systems on P_c are shown in Fig. 7. Here, power loss means [P_{PV} at 1.85 V(300 mW)$-P_c$] for a conventional system, and [P_{PV} at 1.85 V(392 mW)$\times$ duty ratio$-P_c$] for our system. The P_R of our system includes power consumption of the LED and EDLC. The LED consumed only enough current, approximately 1 mA (<2 mW), to monitor the EDLC voltage, and the EDLC consumed power at internal series resistance when charging and discharging currents flowed through the EDLC. The P_R in our system was extremely smaller than that of the conventional system, and it was at least more than one order of magnitude smaller. Thus, the power loss at the remote unit was also decreased significantly in our system.

The consumption power of the power controller circuit was approximately 0.4 W. However, this value is expected to decrease significantly, because the circuit design was not optimized from the view point of low-power consumption in this study.

3.3 System Efficiency

The dependences of the total efficiency of the system (η), and the ratio of η between the new and conventional system on P_c are shown in Fig. 8. Here, the total efficiency is defined as [$\eta = P_c/P_{LD}$]. In a conventional system, η is proportional to P_c and approximately 7% when P_c=300 mW. It is almost equal to that in previous systems, around 6%[3][5]. On the other hand, in our system, η was higher and 6～9% over a wide range of P_c. The ratio of η increased with decreasing P_c: below P_c of around 30 mW it was more than 10-times higher than that in a conventional system. As breakdowns of the maximum total efficiency, the efficiencies of the LD, optical fiber, and PV cell and 28%, 71%, and 46% for our system, and 23%, 71%, and 43% for a conventional system, respectively.

As a reference, the broken line in Fig. 8 shows system efficiency where the consumption power of the power controller circuit (0.4 W) was included, although the circuit design was not optimized from the view point of low-power consumption.

Our optical powering system can supply 300 mW of electricity to a device via a 200 m optical fiber. If the transmitted optical power is increased, it is possible to increase electrical power output to the load equipment. However, in this case, optical-electrical conversion efficiency of the PV cell probably decreases without taking appropriate measures, such as attaching a large heatsink to the PV cell to achieve a better thermal release condition.

4. Conclusions

Our proposed optical powering system achieves high efficiency compared to conventional systems, almost independently of the power consumption of the load equipment. This is achieved by using feedback to control the optical power supply to meet the load requirements when the power consumption changes. A value of 9% is obtained as the maximum efficiency in the system, which can deliver 300 mW of electricity to a device at 200 m. This system is therefore particularly useful for driving remote electrical equipment that has variable power consumption and requires complete electrical isolation and/or immunity from electromagnetic noise.

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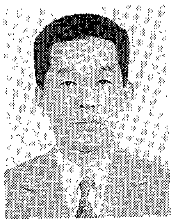

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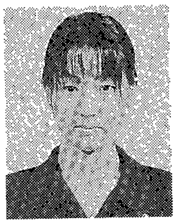

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