Paper

A Stable 2-W Supply Optical Powering System

Non Member **Takako Yasui** (NTT Photonics Laboratories)
Non Member **Junichi Ohwaki** (NTT TelecommunicationsEnergy Laboratories)
Member **Masato Mino** (NTT TelecommunicationsEnergy Laboratories)

A 2-W supply optical powering system that maintains electrical isolation is described. The output power of this system is stable and higher than that of conventional systems, and is not affected by environmental stresses, such as bends in the optical fiber or increased PV cell temperature, owing to its feedback control function. The system mainly consists of laser diodes, optical fibers, photovoltaic (PV) cells, and a feedback control circuit, and can deliver 2 W of electrical power. In the feedback control circuit, the PV cell output current is compared to the target current, and the laser output is controlled to equalize them. The system also has a safety function that shuts down the laser if an optical fiber is cut. The system was tested under a high-voltage condition, and the results indicate that it will be useful for driving sensors and measurement equipment used in high-voltage environments.

Keywords: Photovoltaic cell, Fiber optics, Energy transmission, Optical powering

1. Introduction

Optical powering is a way of supplying power to equipment while maintaining electrical isolation. Optical powering systems consisting of laser diodes (LDs), optical fibers, and photovoltaic (PV) cells have been studied [1,2]. In such systems, optical power is generated by the LD, transmitted through the optical fiber, and converted into electrical power by the PV cell. The advantages of optical fiber compared with copper wire are high voltage isolation, lightness, resistance against corrosion, and waterproofness. Therefore, these systems can power sensors in water, measurement equipment in severe electromagnetic noise environments, and medical equipment [3-5].

PV cells have been designed to increase optical/electrical conversion efficiency and optical fiber coupling efficiency [6,7], and a system output of 300 mW through 200-m long optical fiber has been achieved [7]. However, this is still not high enough for various kinds of sensors and measurement equipment. The system output, which fluctuates because of bends in the optical fibers and because PV cell temperature increases due to the high-power irradiation, has to be stabilized. A safety function that shuts down the laser if the fiber is cut is also important.

We have designed an optical powering system that can deliver 2 W of electrical power. The system features a feedback control function for the laser output that stabilizes the system output and a safety function that shuts down the laser if the optical fiber in the system is cut. Analyses of the efficiency of components in this system have been carried out. We have used this system to drive a lightning sensor in a high-voltage environment and found that it worked without malfunction.

2. System concept and design

The system consists of five optical powering units, each providing more than 400 mW of electrical output. Figure 1 is a block diagram of the optical powering unit, which consists of an LD, optical fibers, a PV cell, a light-emitting diode (LED), a converter, an encoding circuit, a pin-PD, and the feedback control circuit. Optical power is generated by the LD, transmitted via the optical fiber, irradiated onto the PV cell, and then converted into electrical power. The output voltage of the PV cell is converted into 5 V. Table 1 lists the specifications of the unit components. For high optical power transmission and high

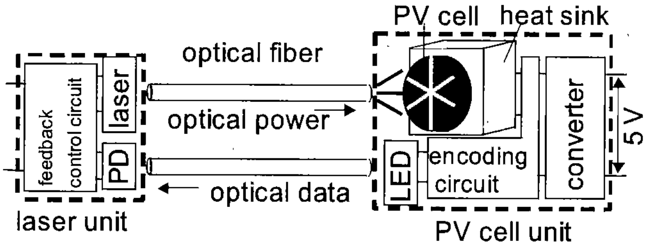


Fig. 1 Block diagram of an optical powering unit.

Table 1 Specifications of unit components.

laser diode	λ = 808 nm, Pmax = 3 W
optical fiber	core / clad 200 / 230 μm λ = 200 m
photovoltaic cell	GaAs, diameter = 3 mm 6 segments, Voc > 5 V

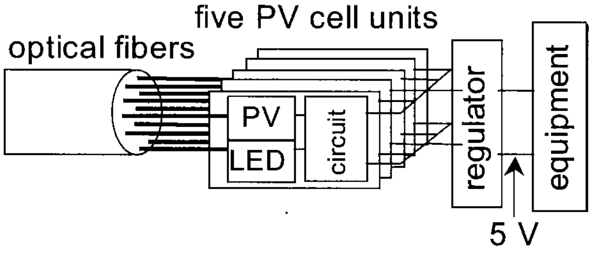


Fig. 2 Composition of PV cell units.

coupling efficiency, we used step-index-type silica fibers with 200/230 μm core/clad diameters and 0.37 numerical aperture, which are larger than those of fibers used in telecommunications. For high transmission efficiency, we used an AlGaAs semiconductor laser diode with 808-nm wavelength, which is located in low transmission loss range of the optical fiber. Its maximum output is 3 W. The GaAs–based photovoltaic cell has high external quantum efficiency at around 800 nm. The PV cell has a round shape and is divided into six segments by trenches. The segments are connected in series to increase the output voltage of the PV cell. It provides more than 5 V output. Each segment is irradiated equally by light from the optical fiber, so that there is little difference in photocurrent among them. Thus, we obtained not only high optical fiber coupling efficiency but also high optical/electrical conversion efficiency by using this PV cell.

The feedback control function operates as follows. Electrical signals whose pulse width is determined by the PV cell output current are generated in the encoding circuit and converted into optical pulse signals by the LED. Optical signals are then transmitted to the laser unit via the optical fiber and converted into electrical pulse signals by the pin-PD. In the feedback control circuit, the output current is compared to the target current, which is set according to the power consumption of the equipment. The laser driver in the feedback control circuit adjusts the laser output to equalize the PV cell output current to the target current. Because the optical fiber transmission doesn't affect the pulse width, signals are decoded completely by the pin-PD. The wavelength of the LED is 870 nm, which is in the range for low transmission loss of this fiber.

The safety function is implemented in the feedback control circuit. In the circuit, the PV cell output current is compared to a safety current that can be changed manually. If the optical fiber is cut, the PV cell output current decreases largely or becomes zero. When it falls 1 mA or more below the safety current, the LD shuts down.

By connecting the five units in parallel (Fig. 2), the system can produce 2 W. Figure 3 is a photograph of the 2-W optical powering system. Each laser unit has a monitor that shows the real PV output current, the target current, and the safety current.

3. Experimental results and Discussion

3.1 Consumption power and efficiency of each component

(a) Laser diode The dependence of the LD efficiency (including an LD driver efficiency) on the LD output is shown in Fig.4. The efficiency is estimated by dividing an LD output into an input power of an LD driver. The LD efficiency increases with increasing LD output and it reaches 17 % when the LD output is 3 W.

(b) Optical fiber The transmission loss of the optical fiber depends on the wavelength of the LD. In this system, we used AlGaAs LDs with 808-nm wavelength, and the transmission loss of this system was measured to be 2.1 dB/km. We also measured the coupling efficiency of the LD and the optical fiber, which depends on the numerical aperture of the opti-

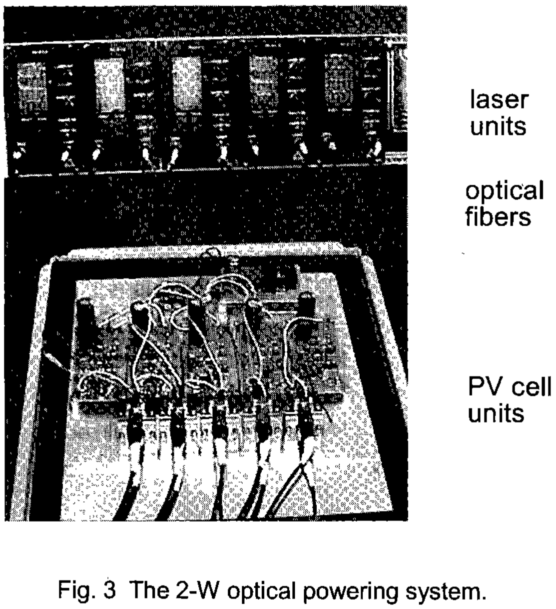


Fig. 3 The 2-W optical powering system.

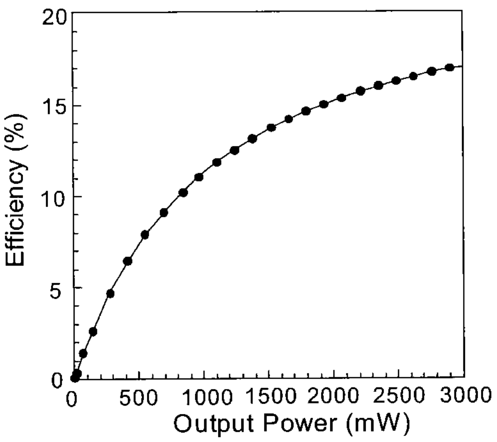


Fig. 4 LD output dependence of efficiency.

cal fiber and the LD. It is approximately 80%.

(c) Photovoltaic Cell unit The current-voltage and power-voltage characteristics of the PV cell are shown in Fig. 5. The solid lines and dashed lines indicate the characteristics at 1.8 W and 700 mW of input optical power, respectively. The short current increases with increasing input optical power of the PV cell. The voltage at the maximum power (Vmax) decreases from 6 to 5.5 V when the input power of the PV cell increases from 700 mW to 1.8 W. The output current of the PV cell decreases sharply when the voltage increases over Vmax. Therefore, the voltage of the PV cell during unit operation has to be below Vmax. Each unit is designed so that the PV cell operates at about 5.2 V. The relationship between the output power and the optical/electrical conversion efficiency of the PV cell in one unit is shown in Fig. 6. The efficiency is around 31% regardless of PV cell output. The efficiency of the PV cell unit, excluding the PV cell efficiency itself, was estimated by dividing the unit output into the PV cell output. The output of one unit is 520 mW at the PV cell output of 560 mW under 1.8 W of PV cell input power. Its efficiency is 93%.

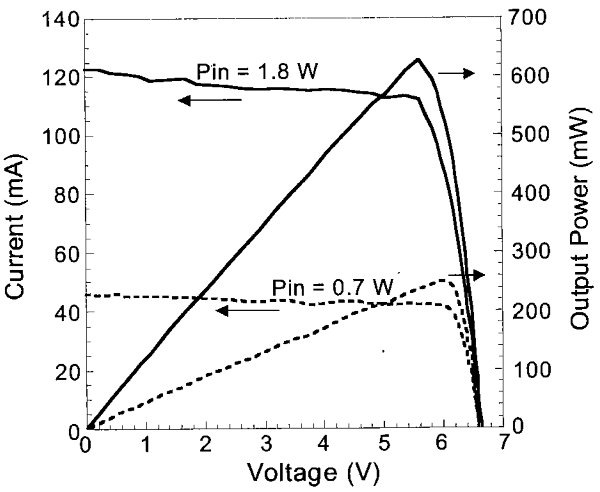


Fig. 5 Current-voltage and power-voltage characteristics of the PV cell.

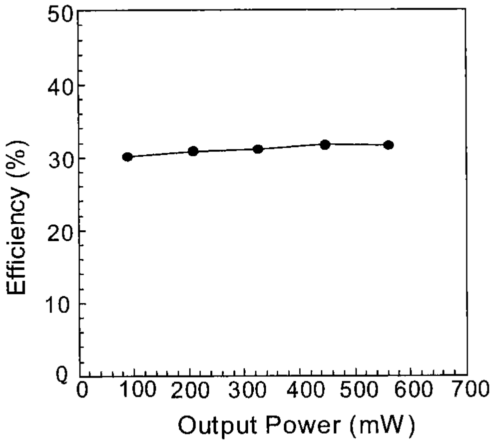


Fig. 6 Output power dependence of the PV cell efficiency.

3.2 Total efficiency

The efficiency for each component at 2 W of system output (the output of one unit is 400 mW) is shown in Fig. 7. The LD efficiency, including the laser driver circuit efficiency, is 15%. The coupling efficiency of the LD and the optical fiber is 80%. The fiber transmission efficiency is 90 % because the trans-

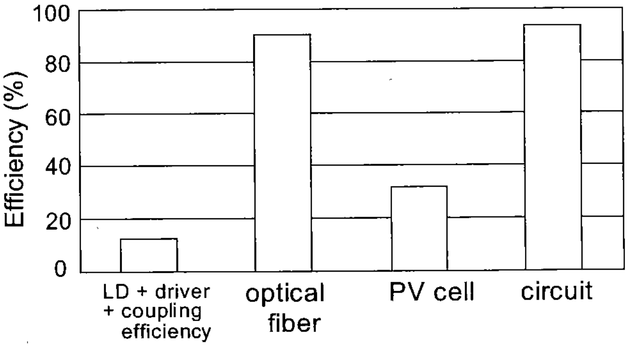


Fig. 7 Efficiency for each component at 2 W output.

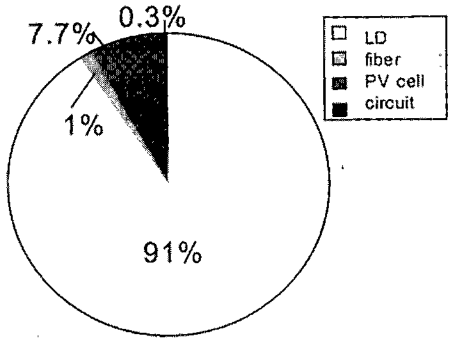


Fig. 8 Power consumption rate of each component.

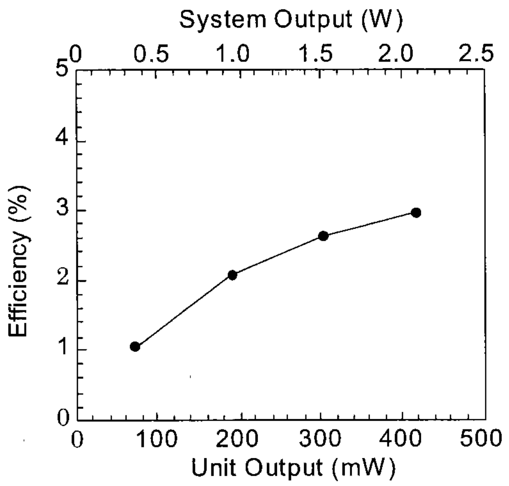


Fig. 9 Efficiency of a unit in the system as the function of output.

mission loss of the fiber is 2.1 dB/km and the fiber length in this system is 200 m. The optical power to the PV cell is 1.4 W (20 W/cm^2) and the output of the PV cell is 430 mW. Therefore, the efficiency of the PV cell is 31 %. A unit output is 400 mW and the circuit efficiency is 93 %.

Figure 8 shows the power consumption rate of each component. The power consumption of the LD unit, including optical fiber coupling loss, is the largest. The total power consumption rate of other components is under 10%. Therefore, the development of the high efficient LD is important for increasing system efficiency.

Figure 9 shows the efficiency of a unit as a function of unit output. The system output, i.e., total output of five units, is also shown in Fig. 9. The efficiency increases with increasing output. This is due to the laser efficiency, because the efficiency of the LD increases with increasing output, whereas the efficiency of the other components change little when the unit output increases. The system efficiency is 2.9 % at 2 W of system output when the output of each unit is 400 mW. The output voltage of this system is 5 V.

3.3 The feedback control and safety function

The feedback control function was tested. Figure 10 shows the dependence of the PV cell output current on the target current that we set. When the target current was changed from 20 to 80 mA gradually, the PV cell output current followed and became equal to it within several seconds.

The stability of the system output was also tested. Figure 11 shows the system output over time. The temperature of the PV cell increased within several minutes of system operation because of the high-power illumination, which caused a decrease of system output. However, in this system, the cell output current was controlled so that it was stable, and the system output was also stable during system operation. When the fibers were bent, the output was still stable as shown in Fig. 11.

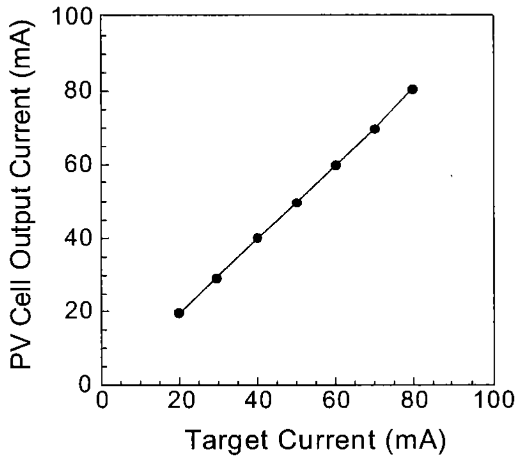


Fig. 10 Target current dependence of PV cell output current.

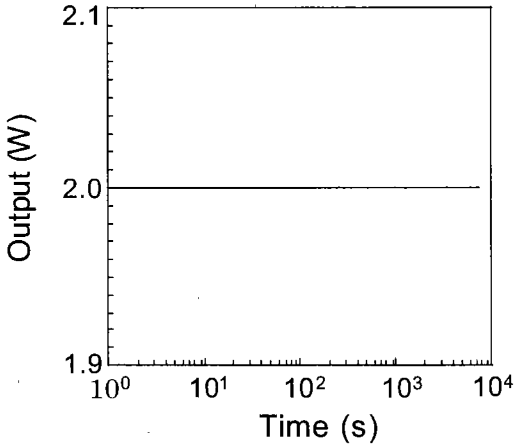


Fig. 11 System output over time.

The safety function was also tested and it operated as expected; the laser shut down when the optical fiber for the power transmission was cut. When the fiber for the optical signals was cut, the laser also shut down because the laser driver could not receive signals.

3.4 System performance under high-voltage environment

We applied this system to a lightning sensor whose power consumption was 2 W. Then, we applied high voltage to a metal wire placed several meters from the optical fiber in our system to create a high-voltage environment. The voltage applied to the metal wire is shown in Fig. 12. The peak of the voltage was 65 kV, and the voltage decreased to half that in 100 ms. In such a high-voltage environment, a power supply system that uses metal wire picks up noise and causes sensor malfunction or breakdown. But the optical powering sys-

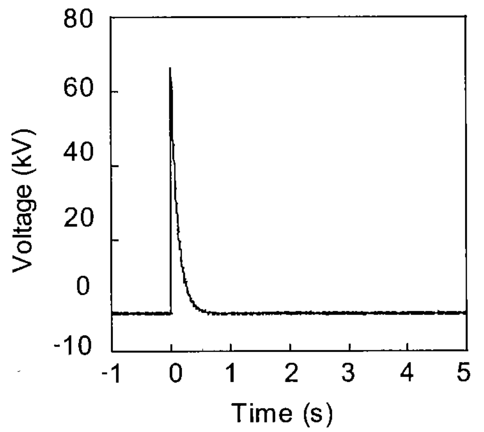


Fig. 12 High voltage applied to a metal wire near our system.

tem continued to supply constant power to the sensor, and the sensor did not malfunction. In addition, the feedback control function of the system worked, and the monitor in the laser unit showed constant PV cell output current. The safety function also worked well. Therefore, we conclude that this system maintains electrical isolation and can supply constant power to lightning sensors on pylons.

4. Summary

We have developed an optical-powering system that can supply up to 2 W of electrical power. The system features a feedback control function and a safety function. The feedback control function stabilizes the system output by adjusting the current to the laser and equalizing the PV output current to the target current set according to the power consumption of sensors. The safety function shuts down the laser when the PV cell output current falls more than 1 mA below the safety current.

We demonstrated the effectiveness of the system by using it to power a lightning sensor and operating it in a high-voltage environment. The results indicate that the system supplies constant power to a lightning sensor while maintaining electrical isolation.

Acknowledgment

The authors thank Mr. T. Tominaga and Mr. N. Kuwabara for their encouragement and discussions.

(Manuscript received October 25, 2001, revised February 14, 2002)

References

(1) Rafael Pena, et al.: "Fiber-Based 205 mW (27 % Efficiency) Power-Delivery System for an All-Fiber Network with Optoelectronic Sensor Units," Applied Optics, 38, No.12, 2463-2466 (1999)

(2) Murphy J. Landry, et al.: "Power-by Light Systems and their Components: an Evaluation," Applied Optics, 30, No.9, 1052-1061 (1991)

(3) Toshiyo Tamura, et al.: "Transcutaneous optical power converter for implantable devices," Proc. SPIE, 2084, 99-104 (1994)

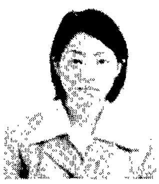
(4) R. Heinzelmann, et al.: "Optically Powered Remote Optical Field Sensor System Using an Electroabsorption- Modulator," IEEE MTT-S, 3, 1225-1228 (1998)

(5) Akira Ohte, et al.: "Optically-Powered Transducer with Optical-Fiber Data Link," Proc. SPIE, 478, 33-38 (1984)

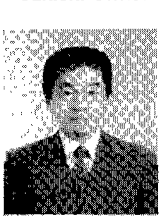
(6) A. Fave, et al.: "GaAs Converter for High Power Laser Diode," 25th IEEE PVSC, 101-104 (1996)

(7) Alan L. Fahrenbruch, et al.: "GaAs- and InAlGaAs-Based Concentrator-Type Cells for Conversion of Power Transmitted by Optical Fibers," 25th IEEE PVSC, 117-120 (1996)

Takako Yasui (Non-member) received the B.S. and M.S. degrees in material science engineering from Waseda University, Tokyo, Japan, in 1994 and 1996, respectively. Since joining the Laboratory system, Nippon Telegraph and Telephone Corporation (NTT) in 1996, she has been engaged in research and development on optical powering systems. Ms. Yasui is a member of the Institute of Electronics, Information and Communication Engineers and the Japan Society of Applied Physics.



Junichi Ohwaki (Non-member) received his B. E., M. E. and D. E. degrees in electrical engineering from Nihon University, Tokyo, Japan, in 1976, 1978, and 1989, respectively. Since joining the Laboratory system, Nippon Telegraph and Telephone Corporation (NTT) in 1978, he has been active in research on thin-film electroluminescent devices and IR to visible upconversion phosphor materials. He is now a Senior Research Engineer of the Energy Systems Labs. in the NTT Telecommunications Energy Laboratories. There, he is currently engaged in research on optical powering systems. Dr. Ohwaki is a member of the Institute of Electronics, Information and Communication Engineers, the Japan Society of Applied Physics, and Phosphor Research Society, The Electrochemical Society of Japan.



Masato Mino (member) was born in Osaka, Japan, in 1958. He received the B. S. and M. S. degrees from Tohoku University, Sendai, Japan, in 1982 and 1984, respectively. He joined Nippon Telegraph and Telephone Corporation (NTT) Electrical Communications Laboratories, Tokyo, Japan, in 1984, where he has been researching soft magnetic materials. Mr. Mino is a member of the Institute of Electrical Engineers of Japan, the Magnetic Society of Japan, and the Japan Institute of Metals.