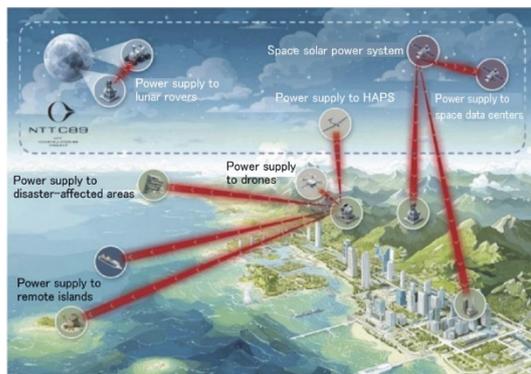


Development of a Laser Wireless Power Transmission System Achieving Stable Power Delivery Beyond 1 km in Outdoor Environments

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Optical wireless energy transmission using lasers is a method that can supply energy to distant locations with high directionality. However, the closer the laser beams are to the ground surface, the more they fluctuate and are more-strongly affected by atmospheric turbulence, leading to a decrease in transmission efficiency, particularly in locations with strong atmospheric turbulence during the day. To address these issues, irradiance at the receiver side was homogenized using a homogenizer with diffuser glass, light was confined using reflectors, and a leveling circuit was applied. As a result, impact from atmospheric turbulence could be reduced, and transmission of 150 W to a location 1 km away outdoors using a 1 kW near-infrared laser was demonstrated ⁽¹⁾.

1. Introduction

Wireless power transmission has been gaining attention as a technology that can deliver energy to remote locations without physical cables. In particular, laser wireless power supply, which transmits energy over long distances using lasers and converts it into electrical energy via photoelectric conversion elements such as photovoltaic (hereinafter referred to as PV) panels, offers advantages such as excellent directionality, the potential for smaller devices compared to microwave wireless power supply, and the absence of electromagnetic interference. A schematic diagram of a laser wireless power supply system is shown in **Figure 1**. The system consists of a transmitter side that controls and emits the laser and a receiver side that receives the laser at a distant location and converts it into electricity. Since no physical cables need to be laid between the two sides, the technology is expected to be applied in disaster-affected areas and remote islands, to power mobile objects such as drones, and even for space applications. To realize these applications, it is essential to transmit energy to distant locations with high efficiency.

Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) is conducting joint research and development of laser wireless power supply with NTT, Inc. (hereinafter referred to as NTT). As mentioned above, while laser wireless power supply offers many advantages, the decrease in transmission efficiency in environments close to the ground surface is a challenge because atmospheric turbulence causes the laser beam to fluctuate like a heat haze.

Output voltage of a single PV cell is typically 1 V or less, so in practical use, multiple cells are connected in series within a PV panel to increase the voltage. Consequently, when the irradiance distribution is not homogeneous, the overall current of the PV panel is limited by the cell with the lowest irradiance and lowest output current among those connected in series, significantly reducing the conversion efficiency of the PV panel. Therefore, irradiating the PV cells with a laser that has an irradiance distribution as homogeneous as possible is essential.

In this joint research, NTT implemented countermeasures against atmospheric turbulence primarily on the laser transmitter side, while MHI focused on the receiver side. On the transmitter side, a transmissive diffractive optical element (hereinafter referred to as DOE) was used to shape

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the beam uniformly. On the receiver side, a homogenizer and a leveling circuit were applied to unify the irradiance distribution of the beam that is distorted by atmospheric turbulence and cannot be fully corrected by the transmitter side alone. This report focuses on measures against turbulence implemented on the receiver side and their results.

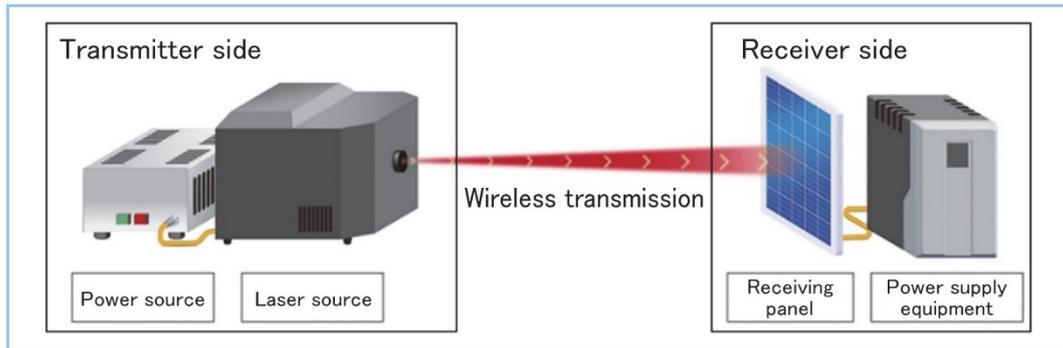


Figure 1 Schematic diagram of laser wireless power supply system

2. Test setup

2.1 System overview

A laser wireless power supply experiment of a distance of 1 km was conducted at the former runway of Nanki-Shirahama Airport in Shirahama, Nishimuro District, Wakayama Prefecture. A laser was horizontally emitted at a height of approximately 1 m above ground level. A photograph of the test setup is shown in Figure 2. The experiment used a single-mode fiber laser with an output of 1 kW and a wavelength of 1,070 nm. The DOE installed at the transmitter side was designed to shape the laser into a homogeneous irradiance distribution after 1 km of propagation. Additionally, a directional control mirror was used to adjust the beam direction for precise irradiation onto the receiving panel. The laser emitted from the transmitter side propagated 1 km through the atmosphere, passed through a homogenizer at the receiver, and then entered the PV panel, where it was output as electrical power.

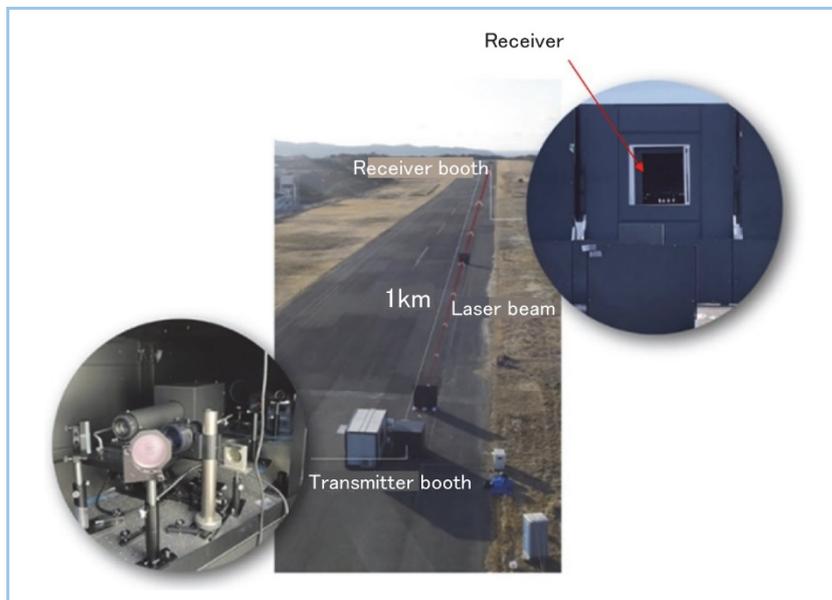


Figure 2 Test setup of the laser wireless power supply experiment with a distance of 1 km

2.2 Receiver overview

A schematic diagram of the receiver is shown in Figure 3. The receiver primarily consists of a homogenizer, reflectors, and a PV panel. While the laser propagates through 1 km of free space, it is affected by atmospheric turbulence, causing the irradiance of the beam reaching the receiver to lose homogeneity, reducing transmission efficiency. To address this, the homogenizer diffuses the light to uniformize the irradiance incident on the PV panel. Furthermore, a structure enclosed by

reflectors is employed to confine the diffused light and prevent its escape outward. Frosted diffuser glass is used for the homogenizer. The distance between the homogenizer and the PV panel was determined based on simulations using the optical analysis software Ansys Zemax OpticStudio.

The PV panel measures 600 mm square and consists of 36-unit cells, each 100 mm square. Low cost, commercially available PERC-type crystalline silicon PV cells were used as the photoelectric elements for solar power generation. Two types of unit cells, Type-A and Type-B with different PV cell connection methods, were used based on the anticipated light receiving intensity. In the central area, where irradiance is expected to be relatively high, 16 Type-A unit cells were placed to suppress the output current, and 20 Type-B unit cells were arranged around them. Type-A consists of four 40 mm square PV cells arranged in a 2×2 array and connected in series, while Type-B consists of a single 80 mm square PV cell. Both Type-A and Type-B reserve a 10 mm margin around the PV cells as wiring space. Reflectors are installed in front of the wiring space, creating a structure that directs laser beams incident on this area toward the PV cells.

Multiple Type-A and Type-B unit cells were connected in series, and output was measured. The specific cells to be connected were determined based on preliminary simulations. Atmospheric turbulence causes fluctuations in irradiance distribution over time, leading to corresponding variations in the output of the PV cells. To mitigate this, a structure that allows a capacitor-based leveling circuit to be connected in parallel to each unit cell was employed. Specifications of the leveling circuit were determined through SPICE analysis using an equivalent circuit model.

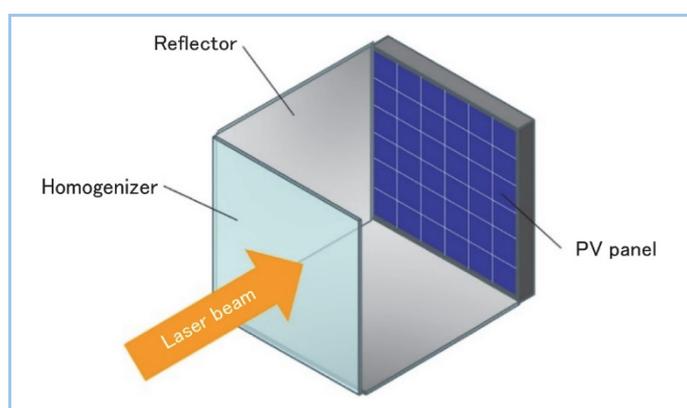


Figure 3 Receiver overview

3. Test results

As shown in **Figure 4**, output power is plotted with respect to the magnitude of atmospheric turbulence when a 1 kW laser, shaped by the DOE, is irradiated onto the PV panel 1 km away. Here, the maximum output that was obtained under low turbulence conditions, with both the homogenizer and the leveling circuit applied as countermeasures against atmospheric turbulence, is set as a reference value of 1. The magnitude of atmospheric turbulence is represented by the atmospheric structure constant C_n^2 [$\text{m}^{-2/3}$], which varies depending on air temperature, solar radiation, and wind speed. Since atmospheric turbulence cannot be controlled, data with high turbulence was measured during the day, while data with low turbulence was primarily measured after sunset. The results from several days were compiled and plotted on the graph.

Also as shown in **Figure 4**, without turbulence countermeasures on the receiver side, output decreases as atmospheric turbulence increases. When only the leveling circuit was applied as the countermeasure, output improved compared to the case without countermeasures. However, the tendency for the output to decrease as turbulence increases could not be suppressed. On the other hand, when both the homogenizer and the leveling circuit were applied, output remained nearly constant regardless of the magnitude of atmospheric turbulence. The temporal fluctuations in PV panel output, when both the homogenizer and leveling circuit were applied, are shown in **Figure 5**. This corresponds to the data point with the highest atmospheric disturbance in **Figure 4**. In this test, a stable power supply with an average value of 150 W over 60 seconds and an efficiency of 15% was achieved.

Although effectiveness is expected to vary depending on the arrangement of the PV cells and the combination of the series connections, a reduction in the impact of atmospheric turbulence caused by the series connection of cells within a PV panel through the use of a homogenizer and a leveling circuit on the receiver side could be demonstrated. The transmission efficiency of 15% achieved in this test is the world's highest for an optical wireless power supply using silicon-based photoelectric conversion elements in an environment with strong atmospheric turbulence.

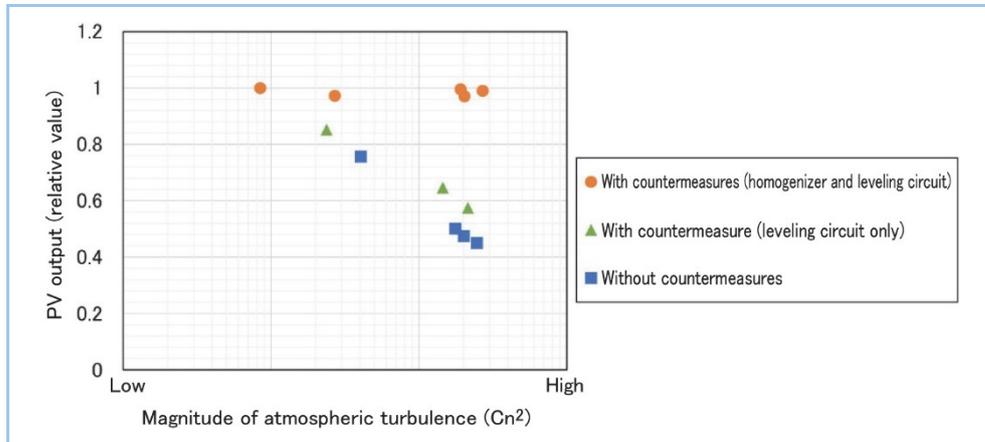


Figure 4 PV output with respect to magnitude of atmospheric turbulence

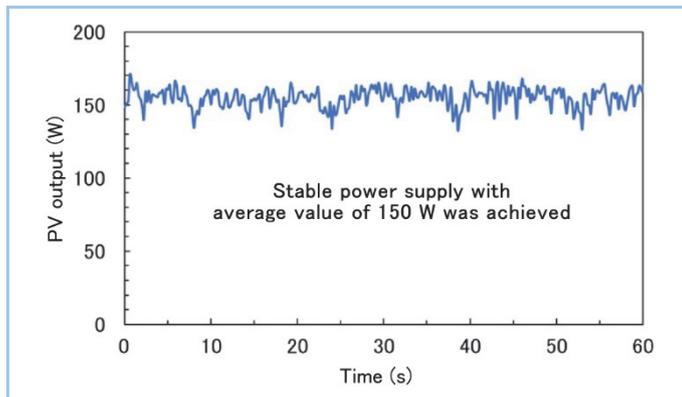


Figure 5 Temporal fluctuations in PV output

4. Future prospects

This technology enables highly efficient and stable long-distance energy transmission even in environments with atmospheric turbulence. While commercially available silicon PV cells were used in this test, by employing photoelectric conversion elements specifically designed for the laser's wavelength, higher power supply efficiency can be expected. In addition, using higher-intensity laser sources would enable the supply of larger amounts of power.

With this technology, flexible and rapid power supply, even to remote locations where installing power cables is conventionally difficult such as remote islands and disaster-affected areas, has become possible. In addition to these terrestrial applications, various other applications based on this technology can be considered. In particular, the high directionality and narrow divergence of laser beams allow receiver devices to be designed smaller and lighter. This offers a significant advantage for mobile platforms with strict constraints on weight and mounting space. For example, by combining this technology with a laser beam direction control technology, power can be supplied to drones while in flight. Wireless power supply avoids operational constraints such as landing for battery replacement or constant power supply via cables, enabling continuous long-endurance and long-range missions. Consequently, previously difficult tasks such as constant monitoring of disaster-affected areas during an emergency and improving communication coverage when relaying wide-area communications in mountainous or maritime regions can be expected.

5. Conclusion

This report presented innovations implemented on the receiver side for a demonstration test of laser wireless power supply technology. This technology has attracted attention as an innovative method to supply power to remote locations, and has achieved the highest efficiency in the world. By applying homogenizer-based homogenization, a light confinement structure, and a leveling circuit, an output of 150 W could be received from horizontal distance of 1 km in an outdoor laser wireless power supply test with a transmission power of 1 kW, despite the use of low cost, commercially available PV panels. In the future, MHI will pursue further miniaturization, weight reduction, and greater improvement in efficiency for practical applications, while also considering laser safety measures.

Finally, the authors wish to express their gratitude to NTT, since the data presented in this report was acquired through collaborative testing with them.

References

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