Space Solar Power System with Optical Technology

Yohei Toriumi, Sho Aonuki, and Madoka Takahashi

Abstract

A space solar power system (SSPS) represents a next-generation energy technology that wirelessly transmits solar energy collected in space to the Earth, offering a stable power supply independent of weather and the day-night cycle. At NTT Space Environment and Energy Laboratories, we are advancing research on solar-pumped lasers, long-distance wireless energy transmission, and high-intensity beam-to-electricity conversion. In this article, we present the development of a photovoltaic cell optimized for 1064-nm laser light. Our prototype device, with an active area of 1 cm^2, achieved world-class conversion efficiency, demonstrating a key step toward practical SSPS implementation.

Keywords: space solar power, laser energy transmission, photovoltaic cell

1. What is a space solar power system?—Space energy lighting the future of the Earth

Global warming, dependence on fossil fuels, resource depletion, and environmental pollution are among the most pressing challenges of the 21st century. One promising technology that has drawn increasing attention as a potential solution is a space solar power system (SSPS). As illustrated in **Fig. 1**, this visionary concept involves wirelessly transmitting energy to the Earth from a large-scale power satellite deployed in outer space. At NTT Space Environment and Energy Laboratories, we are actively conducting research and development to bring an SSPS closer to realization.

1.1 Advantages of generating power in space and transmitting to the Earth

The primary advantage of space solar power lies in its superior power generation environment. Unlike ground-based solar cells, which are affected by weather conditions and the day-night cycle, space-based solar power satellites can directly capture sunlight without atmospheric attenuation. Satellites placed in geostationary orbit (approximately 36,000 km above the Earth) can receive sunlight almost continuously, enabling uninterrupted power generation even when the Earth's surface is in darkness or experiencing adverse weather. As illustrated in **Fig. 2**, space-based systems are estimated to harvest up to ten times more solar energy per unit area compared with ground-based systems.

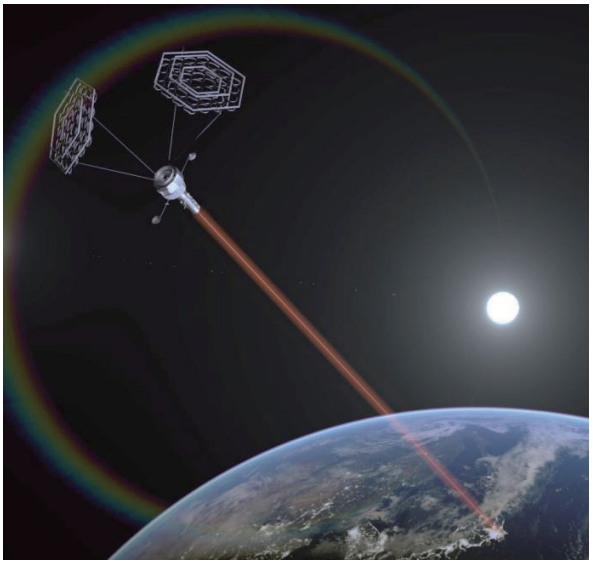

Fig. 1. Conceptual diagram of SSPS.

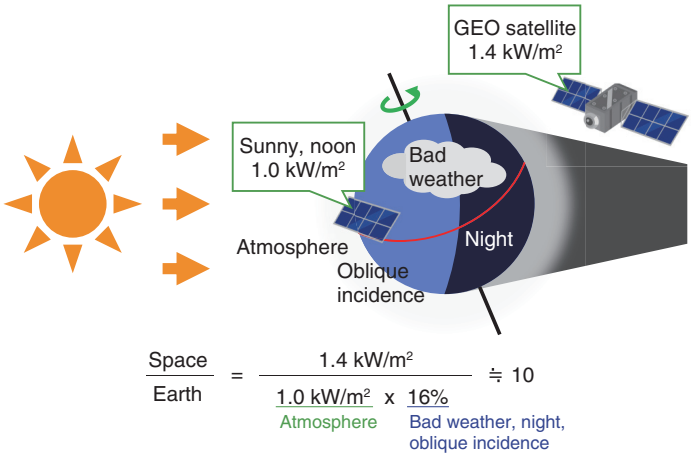

Fig. 2. Estimated energy output from SSPS.

1.2 Wireless energy transmission: Laser-based systems and their advantages

Because power cables cannot be used to deliver energy from space to the Earth, wireless transmission methods are indispensable. For several decades, microwave-based transmission has been the primary focus of research; however, laser-based transmission has emerged as a promising alternative. Due to their shorter wavelength and higher directivity compared with microwaves, lasers enable the use of more compact equipment and allow for highly precise transmission. For instance, while microwave-based SSPSs require antennas several kilometers in diameter on both the transmitting and receiving ends, laser-based systems can reduce the size of both transmitters and receivers to less than 100 meters, thus lowering costs and system complexity. Thanks to the high straightness of laser beams, receivers can be installed closer to consumer areas such as cities or industrial zones.

1.3 Wavelength selection—Three critical factors

Selecting the appropriate laser wavelength is crucial for efficient energy transmission from space to the Earth. Three key factors must be considered:

1. Atmospheric transmission efficiency at the chosen wavelength
2. Conversion efficiency of the photovoltaic cell
3. Beam divergence characteristics

For example, the 0.9–1.1-μm band offers approximately 95% atmospheric transmittance, making it highly suitable for long-distance propagation. At the same time, photovoltaic conversion efficiency depends strongly on the wavelength: shorter wavelengths generally provide higher conversion efficiency but are more vulnerable to scattering and absorption. Because the transmission distance is about 36,000 km, minimizing beam divergence is essential.

Lasers operating near 1 μm are thus regarded as particularly promising, offering high directionality and compatibility with solar-pumped laser excitation. Unlike electrically driven fiber lasers commonly used on the ground, solar-pumped lasers, which directly use sunlight as the pumping source, are considered a promising laser source architecture in SSPSs. Research has demonstrated that these lasers can be tuned to operate close to 1 μm, providing an optimal balance between atmospheric transparency and photovoltaic conversion efficiency.

1.4 Ensuring safety

A primary concern in laser-based space-to-Earth energy transmission is the safety of high-power beams. Accidental exposure could cause serious harm to humans, animals, or the environment. To mitigate these risks, ground-based receiving facilities are designed as enclosed structures that prevent beam misalignment. High-sensitivity sensors are used to detect even minor deviations and immediately shut down the laser if necessary. Safety systems also include monitoring for aircraft and birds, ensuring that energy transmission is permitted only when conditions are confirmed to be safe.

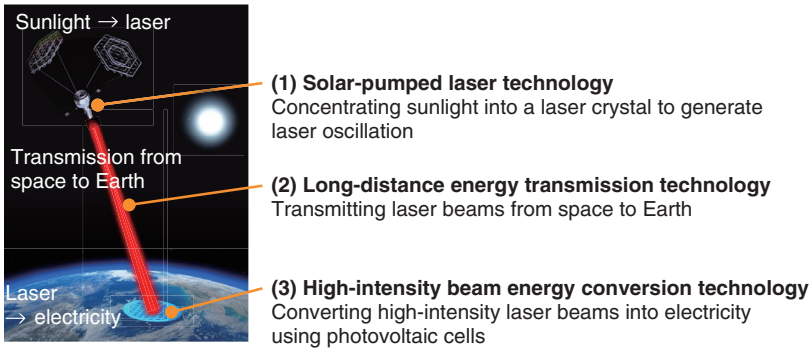

Fig. 3. Three key technologies required for space solar power generation.

1.5 Cost considerations

Technical feasibility alone is insufficient; economic viability is equally essential for the implementation of SSPSs. One of the greatest challenges lies in cost. For example, while electricity generated from fossil fuels is priced at around 0.07 USD per kWh, National Aeronautics and Space Administration (NASA) estimates that by 2050 the cost of terrestrial solar power generation will decline to about 0.02 USD per kWh, whereas the cost of an SSPS will remain above 0.61 USD per kWh—approximately 35 times higher [1].

Advances, however, are steadily improving the outlook. The emergence of reusable rockets, lightweight satellite designs, and high-efficiency solar cells has drastically reduced launch costs—from about 10,000 USD per kilogram in the early 2000s to roughly 3000 USD per kilogram with SpaceX's Falcon 9. If such trends continue, the lifecycle cost of SSPSs has the potential to become competitive with terrestrial power generation.

1.6 Impact on our lives

If successfully implemented, an SSPS could have a transformative impact on society. It would ensure resilient power supplies during natural disasters, provide electricity to remote islands and developing regions where infrastructure is limited, and contribute to global decarbonization efforts by generating energy without greenhouse gas emissions. Beyond its technical advantages, an SSPS carries significant strategic value as a sustainable and universally accessible energy source for the future.

1.7 NTT's research focus

To make an SSPS a reality, it is essential to overcome three major technological challenges, all centered on the efficient use on the Earth of solar energy collected in space (**Fig. 3**).

The first challenge is solar-pumped laser technology, which converts sunlight directly into laser light. Although solar energy is more abundant in space than on the Earth, devices must be built and launched with limited resources, making high conversion efficiency indispensable. Any unconverted energy is dissipated as heat, and low efficiency greatly increases the burden on thermal-management systems. While space solar power is often imagined as using orbital solar cells to generate electricity then using electricity to power lasers, we are pursuing a simpler approach: using sunlight directly as the pumping source to generate laser oscillation without an intermediate electrical stage. To enhance efficiency, we have fabricated promising crystal materials such as Nd/Cr:YAG and Nd/Ce:YAG* and conducted resonator design and solar-pumping oscillation experiments under terrestrial conditions [2].

The second challenge is long-distance energy transmission technology, which ensures that laser light generated in space can be delivered accurately and efficiently to the Earth over a distance of approximately 36,000 km. Although laser beams possess excellent directivity, they gradually diverge over long distances and subject to atmospheric disturbances—known as turbulence—that can prevent precise delivery to receiving panels. To mitigate these effects, we are developing specialized optical elements and

* Nd/Cr:YAG, Nd/Ce:YAG: Crystals with a garnet structure composed of a complex oxide of yttrium and aluminum ($Y_3Al_5O_{12}$), into which neodymium and either chromium or cerium are added to enhance absorption of sunlight wavelengths for use as laser gain media.

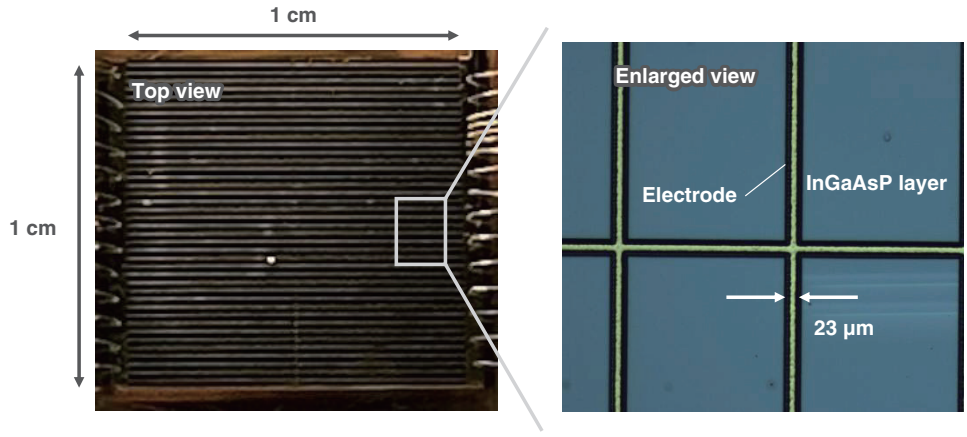

Fig. 4. Enlarged photograph of the fabricated 1-cm² photovoltaic cell.

designs. For instance, we designed laser beams optimized for long-distance transmission using diffractive optical elements and carried out horizontal transmission tests on the ground [3].

The third challenge is high-intensity beam energy conversion technology, which converts the incoming high-power laser into practical forms of energy. Depending on application and installation conditions, conversion into hydrogen or heat—more suitable for storage and transport—may be viable. However, our initial focus is electricity generation, and we are developing advanced photovoltaic cells. To lower power generation costs, we are investigating semiconductor material compositions and designing receiver panels optimized for laser illumination [4].

All three technologies are essential for the implementation of SSPSs. In this article, however, we highlight high-intensity beam energy conversion technology, which has been less frequently introduced. In particular, we report on the development of photovoltaic cells optimized for 1064-nm laser light and present results demonstrating world-leading conversion efficiency.

2. Development of photovoltaic cells for laser reception

2.1 Device technology for converting light into electricity

Photovoltaic cells transform optical energy into electrical power. The most familiar example is the solar cell; however, unlike sunlight—which is broadband and relatively low in intensity—lasers deliver high-power, single-wavelength beams. Consequently, photovoltaic cells designed for laser reception must withstand significantly higher power densities, maintain thermal stability, and be optimized for specific wavelengths. Despite their importance, research and development in this field remains limited, and high-efficiency, large-area photovoltaic cells are still scarce.

2.2 Candidate materials and challenges

For ~1-µm lasers, potential materials include silicon (Si), indium gallium arsenide phosphide (InGaAsP), indium gallium arsenide (InGaAs), indium aluminum gallium arsenide (InAlGaAs), copper indium gallium diselenide (CIGS), and perovskites. Among these, III-V compound semiconductors, such as InGaAsP, exhibit the highest potential for achieving superior conversion efficiency. Notably, previous studies have reported an efficiency of 50.6% at 1064 nm using small-scale InGaAs devices. However, for practical SSPSs, it is crucial to scale up these devices to large-area photovoltaic cells while maintaining high efficiency.

2.3 Fabrication and evaluation of 1064-nm InGaAsP devices

NTT has fabricated a 1-cm² InGaAsP photovoltaic cell optimized for 1064-nm laser reception (**Fig. 4**). The device incorporates a 2-µm InGaAsP light-absorption layer, patterned gold and silver electrodes, and anti-reflection coatings. To minimize shading, electrode coverage was limited to 7%. Unusual thick electrodes (10 µm, approximately 50 times thicker than standard designs) were also adopted to reduce series resistance and enable high-power operation.

Experimental evaluation was conducted using a

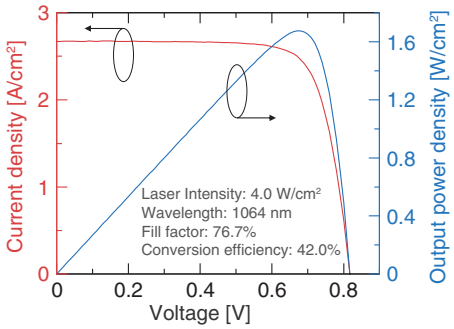

Fig. 5. Measurement results of the fabricated 1-cm² photovoltaic cell.

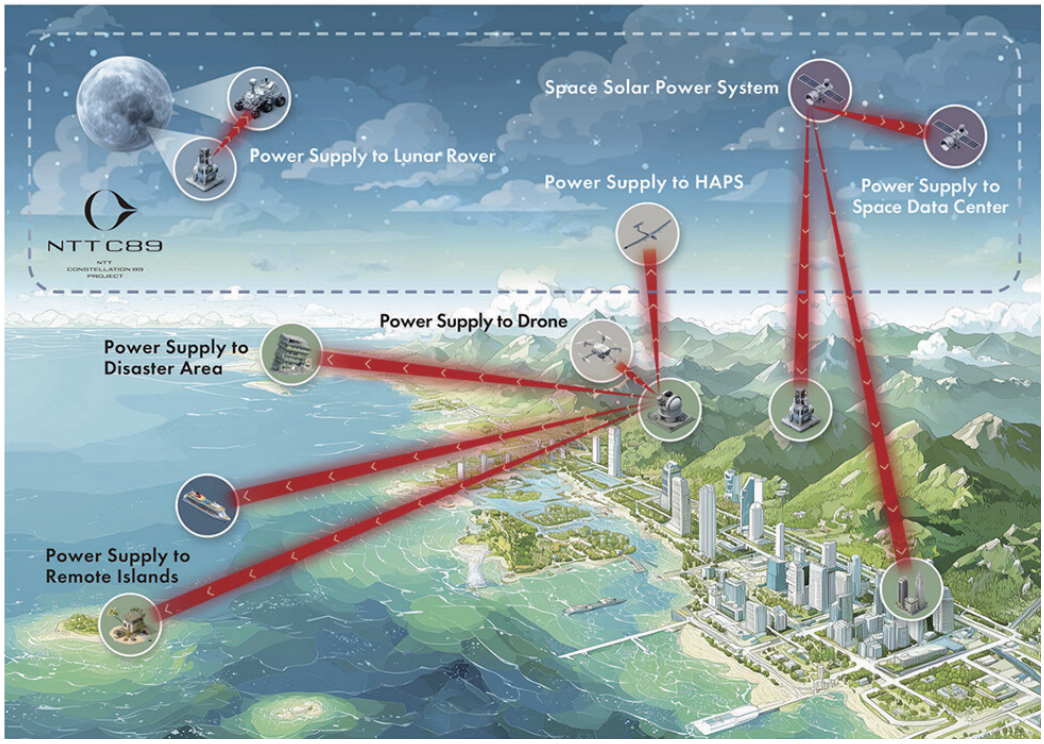

Fig. 6. Application scenarios for SSPS and laser energy transmission.

commercial 1064-nm fiber laser with a beam diameter expanded to 1 cm. A conversion efficiency of 42% was achieved at 4 W/cm^2, representing the highest reported value for a device of this area (**Fig. 5**). A fill factor of 76.9% was also obtained at 3 W/cm^2, significantly enhanced by the adoption of thickened electrodes, which suppressed efficiency degradation under high intensity illumination. Overall, series resistance was reduced by approximately 20% compared with previous devices.

3. Future prospects

In addition to photovoltaic cells, NTT is advancing solar-pumped laser development and long-distance transmission experiments. The potential applications of these technologies extend beyond an SSPS, including terrestrial laser-based wireless power transfer for supplying electricity to remote islands, disaster-stricken areas, drones, and high-altitude platform stations (HAPSs) (**Fig. 6**). Through these innovations,

NTT seeks to accelerate research and development efforts that contribute to a sustainable society.

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