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Wireless Power Transmission of Solar Energy from Space to Earth Using Microwaves

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Abstract- **In the previous stages, we are studying the concept of harvesting solar energy from space using an SSPS (Space Solar Power System). One of the major challenges associated with this technology is the ability to transport collected energy to Earth.**

INTRODUCTION

In this article, we will go over the two major viable methods of space-to-Earth power transmission: lasers and microwaves. We will also briefly discuss a hybrid approach that combines laser and microwave transmission.

Fig: Atmosphere with different layers

Safety of Wireless Power Transmission

In the proposed designs, the laser beams will operate at skin- and eye-safe wavelengths, with intensity comparable to normal sun exposure, and the intensity of the microwave radiation will be about one-sixth of that of noon sunlight. Operating at these levels ensures that either transmission mode will be safe for humans, animals, and plants.

Space Solar Power Transmission

The laser beam and microwave power transmission systems are currently the most promising technologies for wirelessly transmitting power over the long distance from a satellite in orbit to the surface of the Earth. The two methods differ in size, mode of operation, efficiency, and cost.

Laser Beam Wireless Power Transmission:

The term “LASER” stands for Light Amplification by Stimulated Emission of Radiation. Lasers are a form of artificial light with a uniform phase and wavelength.

A core property of a laser is a low divergence angle that spreads out very little as it projects out further from its source. Lasers are also small enough to fit within compact instrumentation, which makes them ideal for inter-orbit optical communication systems and other systems for communicating over long distances. The Laser-based SSPS (L-SSPS) uses these unique properties to send solar-powered laser energy from space to Earth, where it is converted into electricity.

The transmittance of laser beams depends upon their wavelength. The SSPS Research Team has been studying a laser wireless power transmission technology operating at a wavelength of about 1070 nm (near-infrared) and a continuous-wave (CW).

The characteristics of lasers as an energy transfer medium

- Lasers can be fit within compact instrumentation. (This allows us to develop a small SSPS.)
- Lasers cannot penetrate clouds or rainfall.
- Lasers are susceptible to atmospheric disturbances.
- Lasers require stringent safety requirements to protect human eyesight. (Lasers are very hazardous to the human eye.)

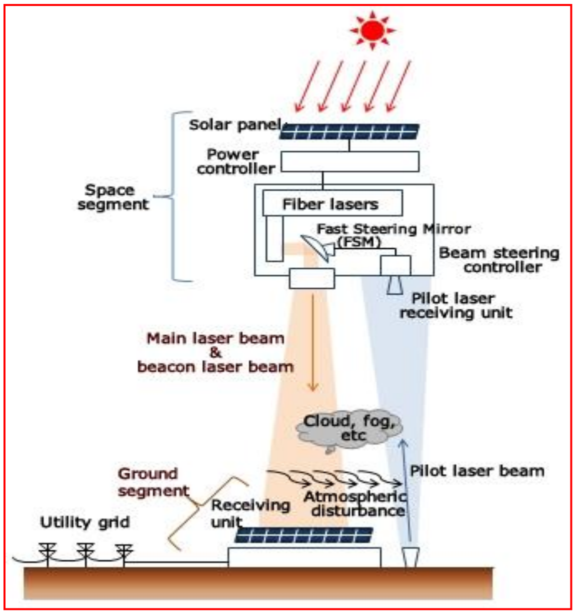


Fig: Leaser beam wireless power transmission

The SSPS Research Team has been researching and developing technology to control the direction of laser beams. A laser beam must be pointed with an accuracy of 1μrad（5.7×10^{-5}deg) to limit the divergence to several tens of centimeters when transmitted from low earth orbit (LEO) at an altitude of several hundred kilometers. When transmitted from geostationary orbit (GEO) located 36,000 kilometers away, it must be pointed with an accuracy of 0.1μrad（5.7×10^{-6}deg) to limit the divergence to several tens of meters. To attain this accuracy, the team selected a beam-steering control method operated by establishing a mutual laser link between the ground and space segments. The ground segment sends a pilot laser beam to the space segment, which sends back a beacon beam based on the angle at which the pilot beam arrives. Next, the high-power main laser beam sends electric power to Earth. The team is now striving to achieve an accuracy of 1μrad as a near-term goal with a view to ultimately realizing an accuracy of 0.1μrad.

Lasers are susceptible to the effect of atmospheric disturbances near the ground. An atmospheric disturbance significantly distorts the pilot beam sent up from the ground to spacecraft, causing spacecraft to detect the arrival angle fluctuations of the pilot beam. The fluctuations can be offset by a Fast Steering Mirror (FSM), a device that rapidly corrects the angular deviation of the beam to ensure that the beacon laser and main laser beams can be directed toward the terrestrial receiving system spot on.

Optical communication links between spacecraft and the ground are established using a similar approach, but the optics for the L-SSPS spacecraft differs in two important ways. First, the instrumentation must be designed to handle a far more powerful class of laser than the lasers used for optical communications. Second, it must transmit energy with extreme efficiency to ensure that the ground receiving system receives most of the laser energy transmitted via main laser beams and converts it into electricity.

Laser oscillator and terrestrial receiving unit

The laser oscillator currently selected for the L-SSPS is the CW fiber laser, a class whose power has been growing exponentially for years. Fiber lasers are used widely in drilling, welding, and other material-processing industries. Powerful types with outputs of up to 10 kw at a 1070 nm wavelength (near infrared) are now commercially available. After further study on the materials, thermal control, and higher outputs and efficiency, these commercial lasers are expected to be adaptable for application in space.

A terrestrial receiving unit must convert laser to electricity efficiently. The SSPS Research Team has been researching high-efficiency conversion of laser with given wavelengths using photoelectric conversion elements such as InGaAs.

Ground demonstration on laser wireless power transmission

Fig: Test Site (JAXA Space Center)

The SSPS Research Team has been working on ground demonstrations of wireless power transmission by laser with a view to achieving high-accuracy beam steering control even under the effect of atmospheric disturbance.

The SSPS Research Team conducted a series of 500-m horizontal laser transmission tests at its test site in 2012 and 2013, demonstrating that the beam could be controlled with an accuracy of 1μrad when atmospheric disturbances were relatively weak. Yet the fluctuations of arrival angle of laser could not be adequately controlled under intense sunshine, a major source of atmospheric disturbances near the ground.

In the next round tests, the team will be transmitting a laser from the top of a 200-meter-high tower to the ground along a pathway similar to the space-to-ground pathway of the L-SSPS. The team expects to achieve stable beam steering control even under intense sunshine because of the shorter time spent passing through the near-ground atmospheric disturbances. The main laser output power will be up to 500 W. A demonstration scheduled to start in FY2016 will target an accuracy of 1μrad.

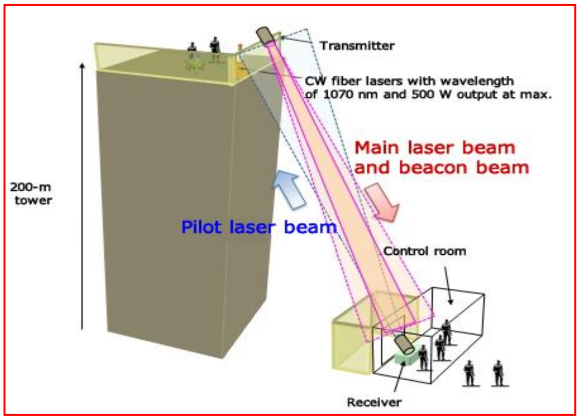


Fig: Ground demonstration on a 200-m vertical laser wireless power transmission

In the laser beam wireless power transmission technique, a laser beam sends concentrated light to a photovoltaic cell receiver through the vacuum of space and the atmosphere. The receiver converts the energy back into electricity through these steps:

1. The DC power harvested in space is used to generate a single wavelength (monochromatic) light beam.
2. A set of optics shapes the laser light according to the required beam size.
3. A control systemensures that the laser is pointed at the intended receiver site on Earth.

The mode of operation of the photovoltaic receiver is similar to that of solar power harvesting in which the sunlight falling on solar cells produces electricity. However, this method uses high-intensity laser beams on specialized photovoltaic cells and allows for higher efficiency than what is currently possible with solar cells. Mirrors and telescopes can be used to aim the laser beam at any receiver directly below the satellite with an unobstructed-line-of-sight transmission path.

Advantages of Laser Beam Transmission

- Does not interfere with TV, radio, Wi-Fi, cell phone and other communication signals
- Requires smaller transmission and receiving equipment compared to microwave transmission. (For example, a 1GW installation would require about a one-meter diameter transmitting optics and a ground receiver of several hundred meters across.)

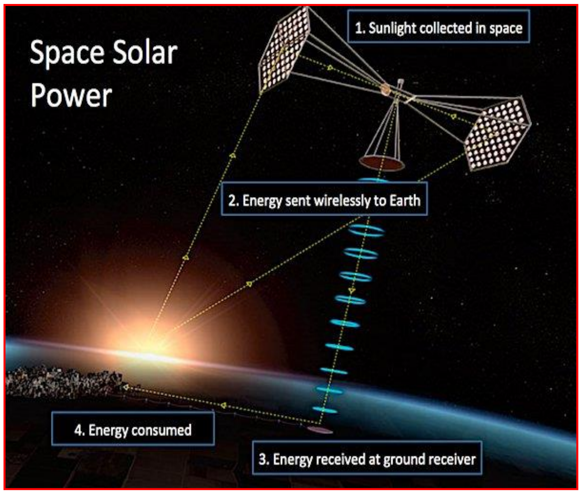
Disadvantages of Laser Beam Power Transmission

- Suffers from atmospheric losses due to environmental factors such as rain and clouds and hence cannot provide continuous power
- Has a low conversion efficiency
- May require huge battery storage systems on the ground
- Carries the risk of causing skin and eye damage if not well managed

Microwave Wireless Power Transmission

A microwave power transmission system consists of the source of the RF energy, a transmit antenna, a transmission medium or channel, and a rectifying antenna usually referred to as the rectenna. The transmission process involves:

1. Conversion of the DC power from solar cells to microwave (RF) energy
2. Generating and concentrating a microwave beam that can be aimed at fixed locations corresponding to the receivers on the Earth's surface
3. Collection of the RF energy and conversion into electricity at the receiver station



The solar arrays attached to a typical satellite generating 1.6GW in space and an average of 1GW on Earth would measure about 5 to 6 square kilometers and use a transmitting antenna array with a diameter of about 1 km. The large transmitter array ensures that the transmitted beam will have low divergence, and lower beam divergence means that the RF energy will be more spatially concentrated when it reaches the surface of the Earth.

The rectenna is made up of an array of dipole antennas, with fast-switching diodes across the dipole elements. The microwave energy induces alternating current in the antennas. This is then rectified by the diodes to produce DC voltage, which can power DC devices or be converted to AC using an inverter. Schottky diodes are preferred because of their low forward voltage drop, which reduces power dissipation, and fast switching speeds.

One of the most efficient frequencies for the microwave beam is 2.45GHz. This frequency is located in an ISM band, allows for low-cost power components, and does not experience significant attenuation from gases or moisture in the atmosphere.

The table below lists various details for four different space-solar-power systems:

Model	Old JAXA Model	JAXA1 model	JAXA2 model	NASA/DOE MODEL
Frequency	5.8 GHz	5.8 GHz	5.8 GHz	2.45 GHz
Diameter of Transmitting antenna	2.6 kmϕ	1 kmϕ	1.93 kmϕ	1 kmϕ
Amplitude taper	10 dB Gaussian	10 dB Gaussian	10 dB Gaussian	10 Db Gaussian
Output power (beamed to earth)	1.3 GW	1.3 GW	1.3 GW	6.72 GW
Maximum power Density at center	63 mW/ cm^2	420 mW/cm^2	114 mW/cm^2	2.2 W/ cm^2
Minimum power Density at center	6.3 mW/ cm^2	42 mW/ cm^2	11.4 mW/cm^2	0.22 W/ cm^2
Antenna spacing	0.75 λ	0.75 λ	0.75 λ	0.75 λ
Power per one antenna (Number of elements)	Max. 0.95 W (3.54 billion)	Max. 6.1W (540 million)	Max. 1.7 W (1,950 million)	Max. 185 W (97 million)
Rectenna diameter	2.0 kmϕ	3.4 kmϕ	2.45 kmϕ	1 kmϕ
Maximum power Density	180 mW/cm^2	26 Mw/cm^2	100 mW/cm^2	23 mW/cm^2
Efficiency	96.5 %	86 %	87 %	89 %

Advantages of Microwave Wireless Power Transmission

- Benefits from highly-developed microwave technology, capable of achieving efficiencies of up to 85%
- Achieves lower atmospheric attenuation

Disadvantages of Microwave Wireless Power Transmission

- Requires management of the energy lost during conversion of DC to microwaves
- May cause RF interference
- Requires large transmission and receiving equipment

Laser–Microwave Hybrid Wireless Power Transmission System

Each of the two wireless power transmission methods, microwave- and laser-based, has advantages and disadvantages. In an effort to devise an optimal system, some researchers have considered a hybrid approach.

In such a system, a laser would transmit power from a solar array to an in-orbit base station (a photovoltaic array platform). The base station would convert energy from the laser into electricity and then into microwave radiation, which is transmitted to the receiver station on Earth. Thus, the laser beam is used where it does not experience significant attenuation from the atmosphere, then transmission changes to microwave radiation, which is much less subject to atmospheric attenuation.

CONCLUSION

The Japan Aerospace Exploration Agency hopes to have a commercial space-solar-power system operational within 25 years. Only time will tell if this is an achievable goal. The technological and economic challenges facing space solar power are far from trivial, and all three proposed methods will require much research and testing before they become feasible solutions for large-scale power generation. But history shows that human beings can accomplish amazing things when sufficient motivation is present.

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