Space Solar Power and Wireless Transmission 1 (2024) 102–107

Contents lists available at ScienceDirect

Space Solar Power and Wireless Transmission

journal homepage: https://www.keaipublishing.com/en/journals/space-solar-power-and-wireless-transmission

Full length article

Terrestrial transparent green energy receiving system designed for Space Solar Power Station

Ruinan Fan, Junlin Mi, Changjun Liu *

School of Electronics and Information Engineering, Sichuan University, Chengdu 610064, China

ARTICLE INFO

Keywords:
Wireless power transmission
Rectenna array
Transparent and environmentally friendly

ABSTRACT

In this manuscript, we proposed the concept of a terrestrial transparent energy receiving system for a Space Solar Power Station (SSPS), aiming at solving the problems of environmental destruction and the waste of land resources caused by the construction of large area rectenna arrays at the traditional terrestrial receiving system. We also fabricated a demonstration model of the new system. The system's energy receiving and converting device consists of many rectenna arrays that are flexible, transparent, and matching network eliminated to harvest the microwave energy averaging about 80 mW/m^2 on the ground from the Solar Power Satellite (SPS). The rectenna unit of the system operates at 2.45 GHz, and the measured RF to DC conversion efficiency reaches 20% at −10 dBm and up to 64.65% at 6.8 dBm. As the rectenna array of the system has the advantages of both microwave energy harvesting and light transmittance, conventional solar panels can be placed underneath to collect sunlight and convert it into electricity. It is also feasible to build "self-powered" smart agricultural greenhouses for vegetable cultivation underneath so that the collected energy can be utilized locally to avoid the waste caused by long-distance transmission. The proposed system is of great significance to the research on environmental protection and efficient utilization of land resources at the terrestrial energy receiving system of the Space Solar Power Station.

1. Introduction

Electricity is an indispensable energy source for the development of the world, and the choice of energy source for power generation is crucial. Compared with the traditional environmentally unfriendly fossil energy and unstable renewable energy, space solar energy has the advantages of abundant reserves and stable radiation intensity [1]. In 1968, Peter E. Glaser first proposed the Solar Power Satellite (SPS) concept to exploit space solar energy for human beings [2].

The Space Solar Power Station (SSPS) comprises a space transmitter and a terrestrial energy-receiving and converting device. The SSPS converts the space solar energy into electrical energy and then into microwave energy. The rectenna arrays on the ground harvest and convert the microwave energy through wireless energy transmission into DC power. At present, the United States, Japan, China, and European countries have put forward development plans and design schemes for the construction of space solar power stations and have carried out preliminary experimental verification [3–5].

Rectennas are an essential part of an MWPT system [6]. Considering that the ground receiving end of the SSPS needs a large area to build the rectenna arrays and the low receiving power density of 80 mw/m^2 on average, the rectenna units should have a relatively simple structure and high rectification efficiency under low power density [7–9]. A conventional rectenna needs an impedance-matching network to match the rectifying circuit with a standard antenna impedance of 50 Ω. However, this inevitably makes the structure of the rectenna more complicated. Therefore, a rectenna design that eliminates the matching network by directly conjugating the diode's impedance with the receiving antenna's impedance is more in line with the needs of SSPS [10].

Rectennas fabricated by conventional substrates are usually large in mass, unbendable, and non-transparent. The large-scale application of such structures in the ground receiving end of the SSPS always causes problems such as manufacturing and transportation difficulties, waste of land resources under the rectenna arrays, and environmental disruption caused by the withering of green vegetation. However, the rectennas based on flexible substrates are flexible and lightweight, which can harvest the environmental microwave energy and simultaneously conform with the carrier to increase the space utilization rate [11,12]. If ITO material is used as the electrical conductor sputtered on a transparent substrate [13], the rectenna array will be transparent, and thus, the land resources under the rectenna arrays can be exploited. This aligns with the original purpose of building SSPS: to solve energy problems, reduce environmental pollution, and exploit natural resources efficiently and rationally.

* Corresponding author.
E-mail address: cjliu@ieee.org (C. Liu).
Peer review under responsibility of Chongqing University.

https://doi.org/10.1016/j.sspwt.2024.09.001
Received 29 July 2024; Received in revised form 28 August 2024; Accepted 3 September 2024
Available online 23 September 2024

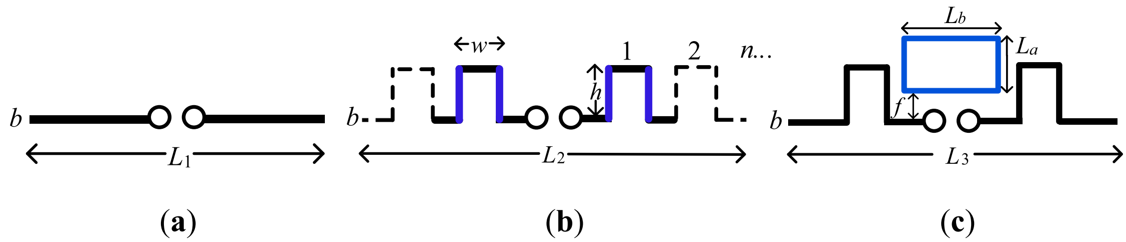

Fig. 1. Dipole antenna (a) Conventional structure; (b) Meander structure; (c) Coupling ring structure.

This manuscript proposes a terrestrial transparent green energy receiving system for SSPS. A demonstration model of the system applied to the intelligent agricultural greenhouse is fabricated. The feasibility of microwave energy harvesting by the transparent and flexible ITO (Indium tin oxide) rectenna constituting the system is also verified. Section 2 discusses the design method of the flexible rectenna, which constitutes the system, and analyzes the measurements of the rectenna. Section 3 describes the composition of the proposed terrestrial transparent green energy receiving system and analyzes the application scenarios with examples. Section 4 analyzes the economic and social benefits of the transparent green energy receiving system and looks forward to the future development and application of the system.

2. Design of the flexible low-power rectenna

2.1. Design of the flexible low-power rectenna without matching network

A conventional rectenna usually consists of a microwave energy-receiving antenna and a rectifier circuit. According to the maximum power transfer theorem, the power transferred to the rectifier circuit is maximized when the receiving antenna's impedance is conjugately matched to the rectifier circuit's input impedance. A conventional way is to design the receiving antenna's impedance as 50 Ω and introduce an impedance-matching network to transform the rectifying circuit's input impedance to 50 Ω. However, the matching network will increase the size and structural complexity of the rectenna, which is unfavorable to large-scale manufacturing for SSPS. Therefore, in this manuscript, the rectenna is constructed by adjusting the receiving antenna's impedance to conjugately match the rectifying diode's impedance directly. This design directly combines the receiving antenna with the rectifying diode, eliminating the matching network and greatly simplifying the circuit's structure.

The half-wavelength dipole antenna is one of the most widely used antennas in wireless communication, and it has the advantages of a simple structure, wide bandwidth, and high gain. It is suitable for the terrestrial energy receiving and converting system of SSPS.

As shown in Fig. 1(a), a conventional half-wave dipole antenna has a length of $L_1 = 1/2\ \lambda$ and consists of two straight metal conductors. The input impedance of a conventional half-wave dipole antenna at 2.45 GHz is (73+j42.5) Ω, which is lower than a rectifying diode's input impedance.

Fig. 1(b) shows meander structures, which allow the antenna to be more compact and increase its reactance. The input impedance of the dipole antenna with four meanders is shifted to (31+j179) Ω at 2.45 GHz [14]. However, the change in impedance by simply increasing the number of meanders or adjusting the length and spacing of the meanders is limited and cannot accurately achieve a conjugate impedance match to the rectifying diodes.

The coupling ring is a closed metal ring that mutually couples electromagnetic fields with the meander dipole antenna. Fig. 1(c) shows coupling ring structures. The input resistance and reactance of the antenna are increased by decreasing the distance f between the coupling loop and the straight arm of the meander antenna. Meanwhile, the reactance of the antenna impedance is tuned almost independently by adjusting the length L_a or width L_b of the coupling loop. The coupling ring structure allows better impedance matching with the diode [14].

The input impedance of the rectenna is simulated by HFSS (High-Frequency Structure Simulator), and the optimized simulation results are shown in Fig. 2(a). At 2.45 GHz, the input impedance of the antenna is (82.4+j 276.05) Ω, an ideal value that can be conjugately matched with the diode impedance.

Table 1
Parameters of SMS-7630 diode.

V_{bi}/V	V_{br}/V	C_{j0}/pF	I_S/μA	R_S/Ω
0.18	2	0.14	5	20

Table 2
The input impedance of the meander line dipole antenna and SMS-7630 diode.

Component	Frequency/GHz	Impedance/Ω
Meander-line Antenna	2.45	82.4+j276.05
	4.9	29.6–j251.4
SMS-7630	2.45	74.41–j265.3
	4.9	23.4–j109.3

2.2. Fabrication and measurement of the rectenna

An SMS-7630 Schottky diode from Skyworks is selected to build the rectenna. Its main parameters are shown in Table 1. Due to its small zero-bias junction capacitance, low on-state voltage, short transit time, and low cost, it is suitable for low-power microwave ambient energy harvesting for the ground receiving end of SSPS.

The simulation results of the diode impedance based on the ADS (Advanced Design System) software with the nonlinear SPICE model are shown in Fig. 2(b) and Table 2. At 2.45 GHz, the impedance of the SMS-7630 diode is (74.41–j265.3) Ω, which can be conjugately matched with the proposed antenna.

The geometry and configuration of the proposed conformal meander dipole rectenna with a coupling ring are shown in Fig. 3. The dimension of the rectenna is 11.1 mm by 36 mm. The top layer of the rectenna is polyimide cover film with a thickness of 12.5 μm and a relative dielectric constant of 2.9. The middle layer uses 18 μm thick copper as the radiator. The dielectric substrate is 25 μm thick polyimide.

The SMS-7630 diode is placed at the feed port of the dipole antenna to convert the harvested RF power into DC power. Two inductors (820 nH) are placed at both ends of the meander line dipole antenna to block RF components.

Fig. 4 shows the fabricated prototype of the rectenna unit. The wires are soldered to the ends of the two inductors as DC outputs. The weight of a single rectenna unit is only 0.12 g.

The proposed flexible rectenna was measured in an anechoic chamber, as depicted in Fig. 5. The 2.45 GHz RF signal is generated by a signal source, amplified by a power amplifier, and transmitted by a standard horn antenna with a gain of 12.95 dB. The power meter (Mini-Circuit) connected to the 30 dB directional coupler was used to measure the transmitted power. The rectenna unit harvested energy at a distance of 1.3 m (far field region) from the horn antenna. The output

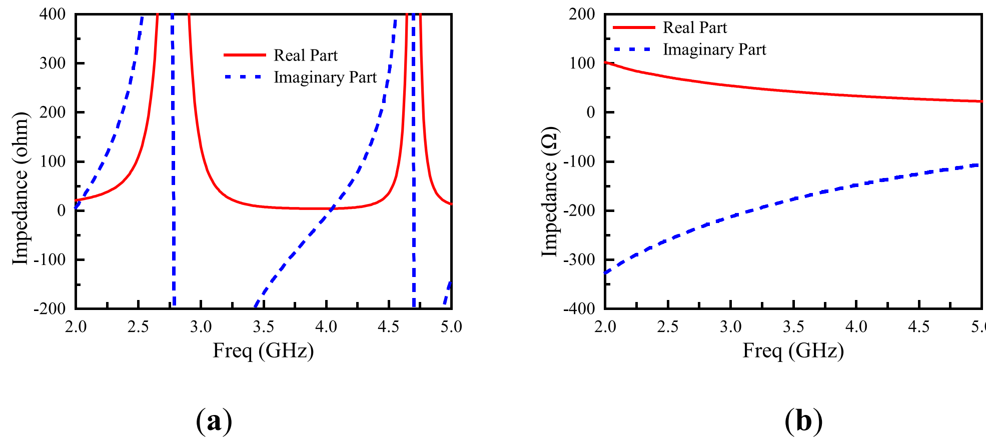

Fig. 2. Impedances of the meander dipole antenna and diode (a) HFSS simulation results of the antenna; (b) ADS simulation results of the diode.

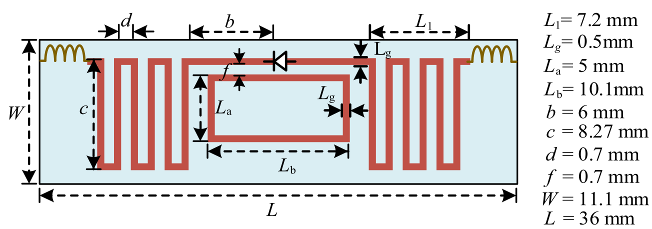

Fig. 3. Geometry and configuration of the proposed rectenna.

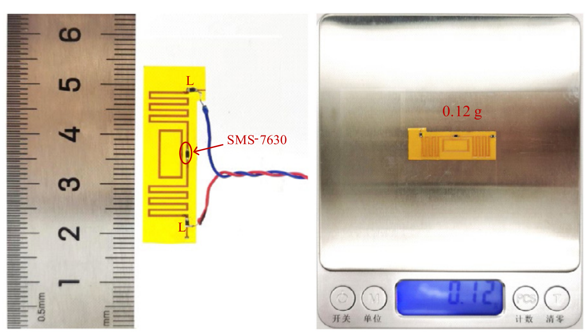

Fig. 4. Fabricated prototype rectenna.

DC voltage (V_{dc}) was measured by a multimeter, and the output DC power was calculated from $P_{out} = V_{dc}^2/R_{load}$.

The received power P_r of the flexible rectenna unit can be calculated by formula (1).

$$P_r = A_e S_{avg} = \frac{G_t P_t A_e}{4\pi R^2} \tag{1}$$

where A_e is the effective area of the antenna, S_{avg} is the average power density at the surface of the rectenna, G_t is the dimensionless horn antenna's gain, P_t is the transmit power measured by the power meter, R is the distance between the transmitting and receiving antenna. We approximate the effective area A_e by the actual physical area of the rectenna. The value of A_e is 7.7 cm^2.

The RF-to-DC conversion efficiency is:

$$\eta = \frac{V_{dc}^2}{P_r \times R_{load}} \times 100\% \tag{2}$$

The relationship between the load and the conversion efficiency is shown in Fig. 6(a) when the received power of the rectenna is 7.4 dBm at 2.45 GHz. It shows that with the increase of the load, conversion efficiency first rises and then decreases. When the load is 300 Ω, the measured maximum conversion efficiency is reached, the output DC voltage is 1.08 V, the output DC power is 3.89 mW, and the conversion efficiency is 64.19%.

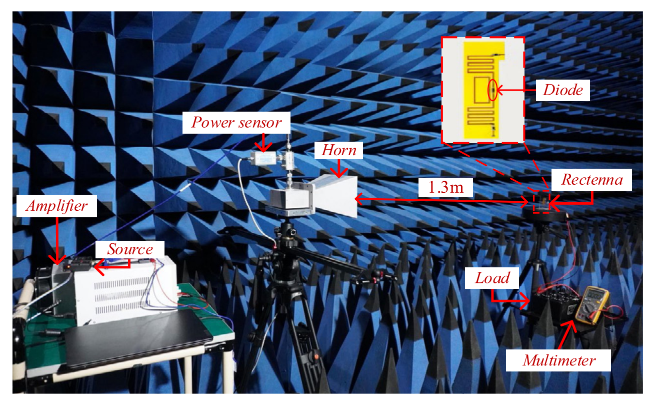

Fig. 5. The test system of the rectenna unit.

The rectenna conversion efficiencies versus the received power at 2.45 GHz with a DC load of 300 Ω are shown in Fig. 6(b). The results show that as the input power P_r increases, the conversion efficiency increases first, reaches the peak, and then drops. The measured highest conversion efficiency of 64.65% is achieved at 6.8 dBm input power, and the output DC voltage is 0.966 V. The measured conversion efficiency reaches 20 % at −10 dBm.

3. Construction of the terrestrial transparent green energy receiving system

3.1. Design and measurement of the transparent ITO rectenna

Indium tin oxide (ITO) is a ternary composition of indium, tin, and oxygen in varying proportions. It has both electrical conductivity and optical transparency. It deposits easily as a film and is chemically resistant to moisture.

The fabricated prototype of the transparent film rectenna using ITO as the electrical conductor proposed in this paper is shown in Fig. 7. It has the same geometry and configuration as the rectenna in Fig. 3. This transparent rectenna uses a flexible transparent PET material with a thickness of 0.188 mm ($\varepsilon_r = 3$, $\tan\delta = 0.06$) as the dielectric substrate. 185 nm thick ITO with 87 % optical transmittance and 6–8 Ohm square resistance was sputtered on the substrate as the radiator. Due to the low melting point of PET material, we used conductive silver paste to solder the SMS-7630 diode to the rectenna as a rectifier.

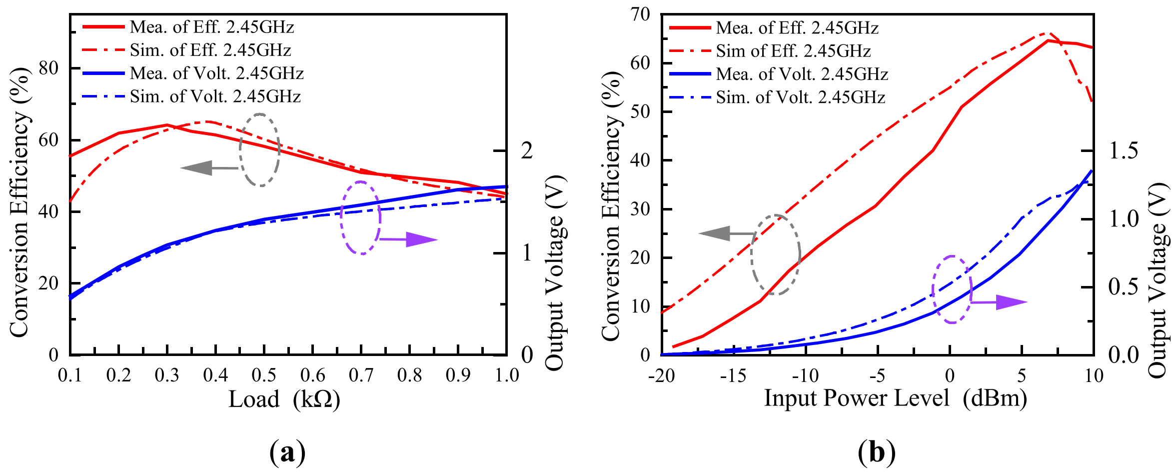

Fig. 6. Rectenna unit simulation and measurement (a) Conversion efficiency with different loads; (b) Conversion efficiency with different input power.

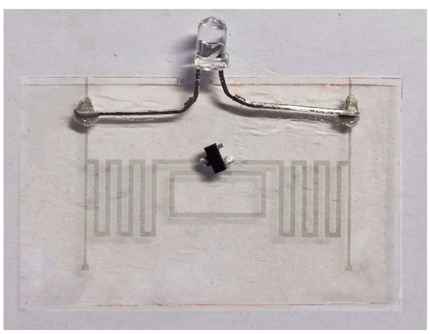

Fig. 7. Fabricated prototype transparent ITO rectenna.

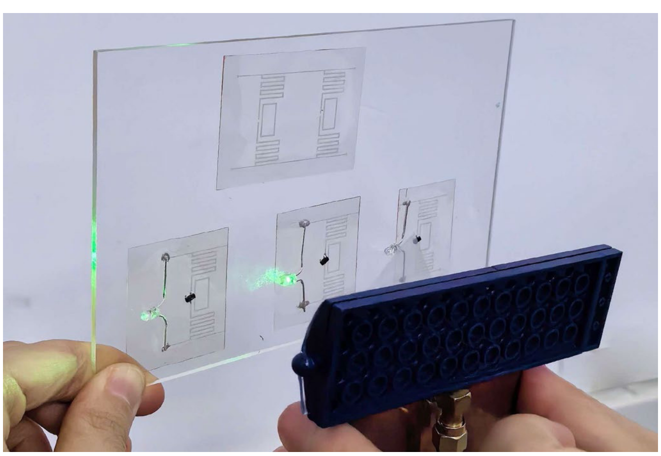

Fig. 8. Transparent rectenna rectification feasibility test.

In order to visually verify the rectification feasibility of the transparent ITO film rectenna, conductive silver paste is used to solder an LED at the DC output of the rectenna. The rectification feasibility test model of the transparent rectenna is shown in Fig. 8. The DC power converted by the rectenna can successfully light up the Light Emitting Diode (LED) at the received power density of 1.8 mW/cm^2. This demonstrates the feasibility of a flexible thin-film rectenna made of ITO materials.

3.2. Construction of the terrestrial transparent green energy receiving system

Since the proposed ITO transparent thin-film rectenna has a simple structure and is capable of wireless energy harvesting and conversion,

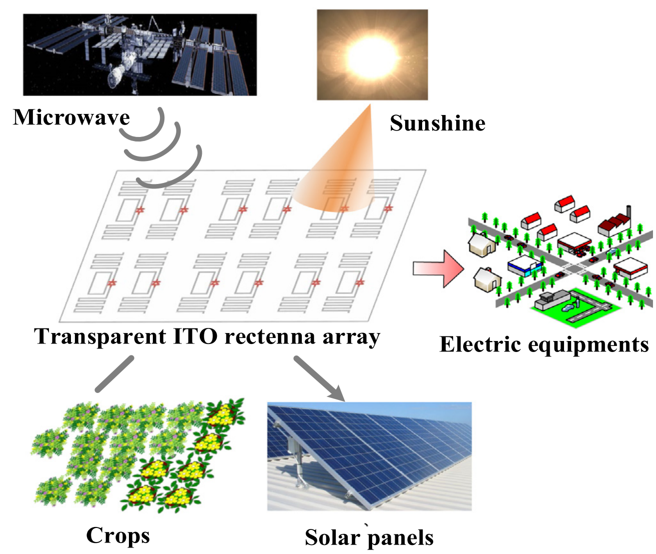

Fig. 9. Terrestrial transparent green energy receiving system.

the transparent rectenna units can be composed of rectenna arrays and mass-produced for the terrestrial energy receiving end of SSPS. The conceptual model of the terrestrial transparent green energy receiving system is shown in Fig. 9. Due to the rectenna arrays being light transparent, it is feasible to build "light-demanding" industries, such as conventional solar panels or agricultural cultivation systems, underneath the large-area transparent rectenna arrays. This avoids the waste of large areas of solar energy resources and improves the utilization rate of the land resources.

Fig. 10 shows a model of the application of the terrestrial transparent green energy receiving system for smart agricultural cultivation. The smart agricultural greenhouse system is constructed at the ground receiving end of the SSPS. A transparent thin-film ITO rectenna array is placed on the outside of the greenhouse to collect microwave energy from the SPS, and the inner surface of the greenhouse is covered with ITO conductive film for electromagnetic shielding to ensure safety.

The advantages of the system are: (1) Transparent film rectenna arrays have good light transmittance which does not affect the photosynthesis of crops. (2) The collected and transformed energy can be directly used as the power supply for smart agriculture, which significantly improves the utilization of energy and avoids the waste of resources and power caused by long-distance power transmission

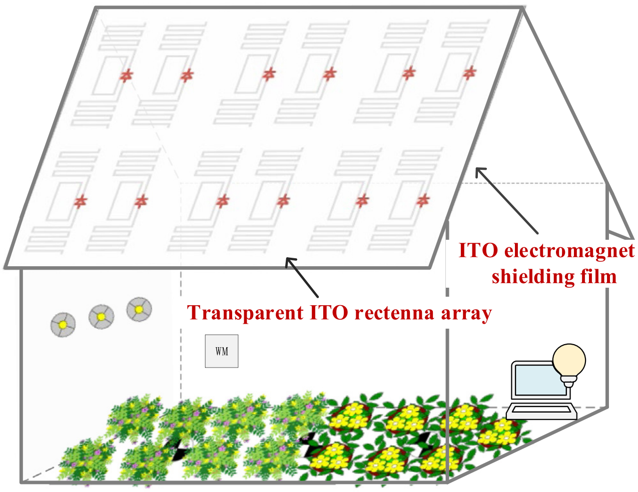

Fig. 10. Terrestrial transparent green energy receiving system applied to smart agriculture greenhouse.

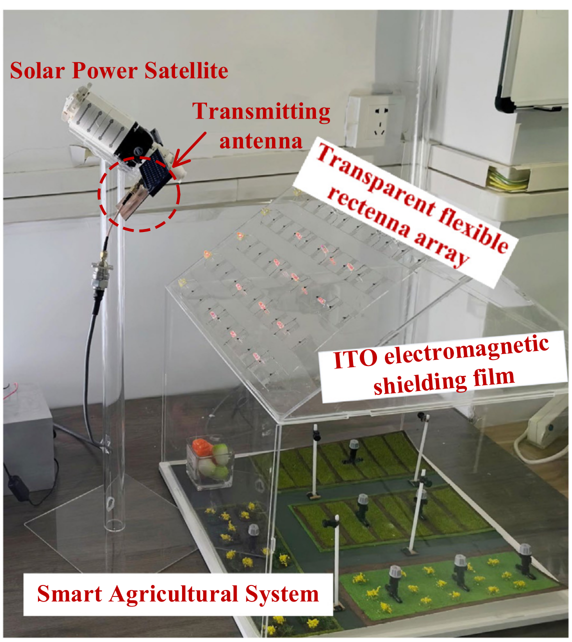

Fig. 11. Demonstration model of the smart agriculture system.

Fig. 11 shows a demonstration model of the transparent green energy-receiving device applied to an intelligent agricultural system. The rectenna array on the outer roof of the agricultural greenhouse can light up the LEDs, which proves the feasibility of energy harvesting and conversion in this way.

4. Benefit analysis of the terrestrial transparent green energy receiving system

The advantages of the transparent green energy receiving system are: (1) As the ground receiving end of the SSPS, the microwave energy from the Solar Power Satellite is converted in high efficiency. (2) Improve the utilization of land resources and make it environmentally friendly (see Fig. 12).

Due to the large area of the ground receiving end of the SSPS, either the crops produced by the intelligent agricultural system or the electricity converted by the solar panels under the transparent

Fig. 12. Future perspectives on transparent green energy receiving system.

rectenna arrays can generate significant economic benefits. Wireless power transmission techniques have a lot of potential applications in space and on the terrestrial level [15–17]. Meanwhile, the transparent green energy receiving system also has good social benefits, which are in line with the trend of environmental protection and rational development of land resources. As an essential part of SSPS, it has educational significance and a vast potential market development value in the future.

5. Conclusion

This manuscript presents a concept of a terrestrial transparent green energy receiving system for SSPS that combines the advantages of energy harvesting and light transmittance. The microwave energy transmitted by the Space Power Satellite can be collected through the rectenna arrays, while the land resources underneath the arrays can be exploited and utilized. Due to the impermeability of light, it solves the problem of environmental pollution caused by conventional large-scale rectenna arrays. At the same time, it can make secondary use of land resources, which has good economic value and social benefits.

CRediT authorship contribution statement

Ruinan Fan: Writing – original draft, Validation, Investigation. **Junlin Mi:** Writing – original draft, Validation, Investigation. **Changjun Liu:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Changjun LIU reports financial support was provided by Sichuan University. Changjun Liu reports a relationship with National Natural Science Foundation of China that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is supported in part by the NSFC U22A2015, 62071316, and Sichuan Science and Technology Program under Grant 2024YFHZ0282.

References

[1] B. Anderson, Solar energy: fundamentals in building design, 1977.
[2] Peter E. Glaser, Power from the sun: Its future, Science (1968) 857–861, 162.3856.
[3] Straub J. Bergsrud C, A space-to-space microwave wireless power transmission experiential mission using small satellites, Acta Astronaut. 103 (2014) 193–203.
[4] B. Duan, Y. Zhang, G. Chen, et al., On the innovation, design, construction, and experiments of OMEGA-based SSPS prototype: The sun chasing project, Engineering (2023).
[5] S. Sasaki, K. Tanaka, K. Higuchi, et al., A new concept of solar power satellite: Tethered-SPS, Acta Astronaut. 60 (3) (2007) 153–165.
[6] 65, A novel single-diode microwave rectifier with a series band-stop structure, IEEE Trans. Microw. Theory Tech. (2) (2017) 600–606.
[7] Z. He, H. Lin, C. Liu, A novel class-c rectifier with high efficiency for wireless power transmission, IEEE Microw. Wirel. Compon. Lett. 30 (12) (2020) 1197–1200.
[8] Z. He, C. Liu, A compact high-efficiency broadband rectifier with a wide dynamic range of input power for energy harvesting, IEEE Microw. Wirel. Compon. Lett. 30 (4) (2020) 433–436.
[9] Z. He, J. Lan, C. Liu, Compact rectifiers with ultra-wide input power range based on nonlinear impedance characteristics of schottky diodes, IEEE Trans. Power Electron. 36 (7) (2021) 7407–7411.
[10] C. Song, J. Huang, P. Zhou, S. Carter, Q. Yuan, Y. Xu, Z. Fei, Matching network elimination in broadband rectennas for high-efficiency wireless power transfer and energy harvesting, IEEE Trans. Ind. Electron. 64 (5) (2017) 3950–3961.
[11] Volakis J.L. Vital D, Textile-based large area RF-power harvesting system for wearable applications, IEEE Trans. Antennas and Propagation 68 (3) (2019) 2323–2331.
[12] Kim J., Cha C., Lee K., et al., E-textile-based wavy surface WPT flexible antenna with frequency self-reconfiguration function for batteryless sensor platform, IEEE Sens. J. 23 (2022) 4392–4404.
[13] Mizuhashi M., Electrical properties of vacuum-deposited indium oxide and indium tin oxide films, Thin solid films 70 (1) (1980) 91–100.
[14] Fan R., Mi J., Jing J., et al., Conformal flexible omnidirectional rectenna array designed for application in IoT smart water meters, Prog. Electromagn. Res. C 139 (2024) 159–166.
[15] Shinohara N., History and innovation of wireless power transfer via microwaves, IEEE J. Microw. 1 (1) (2021) 218–228.
[16] Liu C., Lin H., He Z., Chen Z., Compact patch rectennas without impedance matching network for wireless power transmission, IEEE Trans. Microw. Theory Tech. 70 (5) (2022) 2882–2890.
[17] Shinohara N., Trends in wireless power transfer: WPT technology for energy harvesting, mllimeter-wave/THz rectennas, MIMO-WPT, and advances in near-field WPT applications, IEEE Microw. Mag. 22 (1) (2021) 46–59.