# Research Progress and Design Innovation of Radiant Wireless Charging Systems

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**Abstract.** With the rapid development of electric vehicles, drones, wearable devices and underwater sensor networks, the way of energy replenishment has gradually become an important bottleneck restricting their continuous operation. Traditional wired charging is limited by spatial layout and interface lifespan, and near-field coupled wireless charging is difficult to meet the demands of long distance and cross-media. Therefore, the research on radiant wireless charging technologies is particularly necessary. This article provides a review of three types of radiant wireless charging technologies: laser, microwave and ultrasonic. Firstly, three types of radiation-based wireless charging technologies, namely laser, microwave and ultrasonic, were systematically sorted out and compared, and their basic principles, performance characteristics and applicable scenarios were analyzed. Secondly, in view of the deficiency that a single technology is difficult to cover multiple complex environments, a microwave-ultrasonic hybrid wireless power supply architecture was designed, and the corresponding mathematical model was established for simulation verification. Finally, based on the research results, possible future development trends and optimization directions are proposed. These studies reveal the advantages and limitations of different radiative wireless charging methods and explore more practical system solutions across media and multiple scenarios, providing references for subsequent engineering applications and academic research.

**Keywords:** Radiant WPT; Laser microwave and ultrasonic charging; Hybrid wireless energy systems.

## 1. Introduction

Wireless charging is a non-contact way of energy transmission. Wireless transmission devices transmit electrical energy in other forms through transmitters, and then receive it after a long-distance transmission, achieving the effect of non-contact energy transmission [1]. The traditional wireless charging methods are resonant types, including electric field coupling, electromagnetic induction and electromagnetic resonance charging, etc. They are usually used in wireless charging of mobile phones and electric vehicles. However, resonant wireless charging cannot effectively address the charging demands over long distances and in special scenarios such as underwater. Therefore, in recent years, research on radiant wireless charging methods has gradually emerged.

Compared with magnetic coupling resonance technology, radiant wireless charging can achieve energy transmission at the meter level or even longer distances, and is suitable for non-contact energy supply requirements in unmanned aerial vehicles (UAV), remote sensor nodes and special environments. Lasers, microwaves and ultrasonic waves respectively use photons, electromagnetic waves and sound waves as carriers, each with its own advantages and limitations. Lasers have the longest transmission distance and their efficiency is greatly affected by the environment. Microwaves can perform beamforming and are suitable for medium and long distances. Ultrasonic waves have strong resistance to obstacles underwater or in enclosed Spaces. With the diversification of application scenarios, technical challenges such as high power, long distance and dynamic alignment need to be urgently addressed. Therefore, it is necessary to conduct a horizontal comparison and comprehensive evaluation of the three types of radiation schemes.

This paper focuses on sorting out and comparing the current development status of different radiative wireless charging technologies, evaluating their performance in terms of efficiency, transmission distance and environmental adaptability, and designing improvement plans through modeling and simulation discussions. The research objective is to clarify the applicable boundaries of each technology, propose optimization ideas that can take into account both long-distance and cross-media requirements, and provide theoretical support for building a more efficient, flexible and scalable wireless energy supply system.

## 2. The Basic Principle of Radiant Wireless Charging

Radiant wireless charging, based on the principle of far-field energy transmission, can be classified into three major categories. The first type is laser-based radio energy transmission, which mainly uses lasers to emit highly directional light beams. After optical collimation and tracking, the photovoltaic receiver converts the light energy into electrical energy. The transmission efficiency is affected by the optical loss and the characteristics of photovoltaic devices [1].

The second category is microwave-type wireless charging. Directional electromagnetic waves are emitted by using microwave antenna arrays, and the receiving end adopts a rectifier network to recover energy. The adapted frequency band is usually between 1.5 and 5.8 GHz, and it supports beamforming and broadband transmission [2].

The third category is ultrasonic wireless charging. The main principle is that the ultrasonic transducer emits mechanical waves, which propagate underwater or in a closed medium and are then converted into electrical energy by the receiving probe. The frequency is mostly within the range of 40 to 200 kHz, and it has strong environmental adaptability [3].

### 2.1. Principle of Laser Wireless Charging

As shown in Figure 1, the laser wireless energy transmission system mainly consists of three parts: the transmitting unit, the receiving unit and the power conversion unit. The transmitting end first rectifies and filters the alternating current through an AC-DC converter, and then drives the laser to emit a high-brightness laser. After passing through the collimation and orientation device, the laser beam propagates in the air. At the receiving end, the light energy is converted into direct current through the photovoltaic array, and then adjusted to the required voltage of the load by the DC-DC converter. There is no electrical or mechanical connection between the transmission and reception; energy is solely transmitted by the laser beam. With the small divergence Angle and high-power density of the laser, this system can achieve efficient power supply over several meters or even longer distances. The overall efficiency is determined by the conversion level between the power electronic converter (> 90%) and the optoelectronic device (≈50%), and the improvement space needs to be optimized through collaborative efforts in multiple disciplines such as laser sources, optical components, photovoltaic materials, and converter integration.

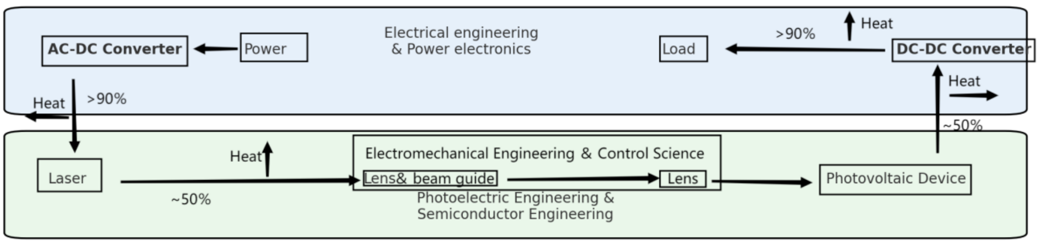


**Fig. 1** Basic Framework of Laser Wireless Charging System [2]

### 2.2. Principle of Microwave Wireless Charging

As shown in Figure 2, the microwave wireless charging system consists of two parts: the transmitting end and the receiving end. The transmitting end first generates a high-frequency and low-power signal from the DC energy through the microwave signal source, and then amplifies it to the watt-level output by the power amplifier. With the application of new semiconductor devices such as silicon carbide and gallium nitride, these solid-state power amplifier devices have performed outstandingly in broadband, high-frequency and high-power scenarios [4][5]. The amplified microwaves are radiated out by high-gain transmitting antennas (such as arrays or reflective surface structures), and phased array technology can be used to automatically track moving receivers, improving directivity and coverage.

The receiving end usually adopts a rectifier antenna to introduce the captured microwave energy into a nonlinear diode for rectification through a wideband matching network and a filter, and then outputs a stable direct current after filtering and voltage stabilization. To balance system compatibility and communication requirements, some designs incorporate duplex functionality into the antenna structure, enabling simultaneous transmission of energy and information across different frequency bands. Although broadband rectifier circuits can receive more spectrum resources, bandwidth expansion often comes at the cost of sacrificing some efficiency. Currently, there are existing solutions to alleviate this contradiction through methods such as circuit coupling and multi-channel parallel connection.

Overall, the core of the microwave wireless charging system lies in how to achieve flexible beam control, wideband reception and stable output while ensuring efficient energy conversion. In actual deployment, the coordinated optimization of component selection, antenna layout and rectifier network are the key to enhancing long-distance power supply capacity.

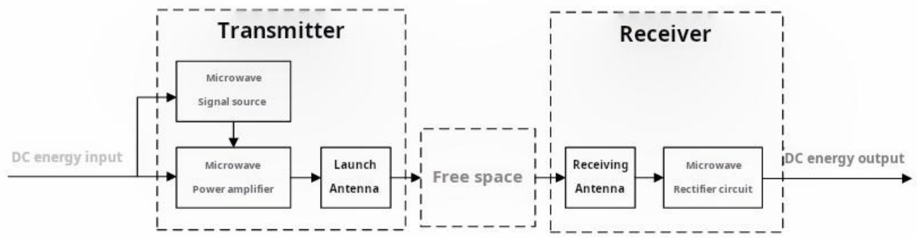


**Fig. 2** Basic Architecture of Microwave Wireless Charging System [4]

### 2.3. Principle of Ultrasonic Wireless Charging

Ultrasonic wireless charging converts electrical signals into high-frequency mechanical waves through ultrasonic transducers. After propagating in air or water media, the energy is recovered by the piezoelectric transducer at the other end and rectified for output. Since the attenuation of sound waves in a medium is related to the square of the frequency, the system usually operates in the tens of kilohertz frequency band and combines array drive to achieve directional energy supply over medium and short distances [6]. In addition, coupling simple data modulation with acoustic energy transmission can achieve synchronous transmission of energy and information on the same channel, providing a new idea for autonomous sensing and communication in underwater and enclosed environments [7].

At present, the design of an ultrasonic wireless charging system is shown in Figure 3. The system includes an ultrasonic electrical energy transmission unit, a transmission probe, a water medium, an underwater receiving probe, a receiving circuit, and an automatic feedback control module. Among them, the ultrasonic emission unit is the core component, responsible for converting the direct current on the primary side into high-frequency ultrasonic vibration through the inverter circuit driven by the optocoupler isolation, and coupling the output to the medium through the probe, wirelessly transmitting the energy to the secondary side probe in a resonant manner. After the secondary side receiving probe captures the vibration, it is restored to direct current through rectification and filtering circuits, and the feedback control module dynamically adjusts the transmission parameters to achieve stable and efficient energy transmission.

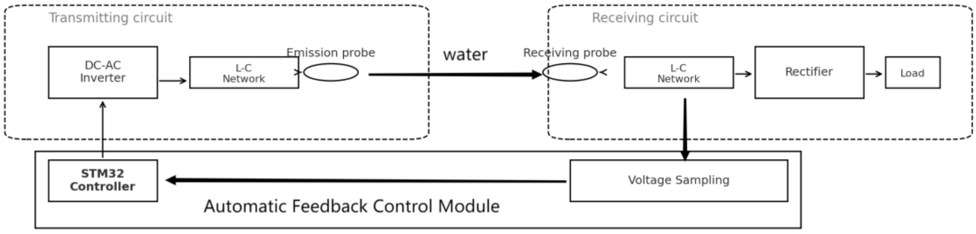


**Fig. 3** Design of an ultrasonic wireless charging system

## 3. Performance Comparison and Comprehensive Evaluation

Table 1 compares the performance of three radiative technologies in typical distance and efficiency.

**Table 1**. Comparison of Three Radiant Charging Technologies

| Type | Effective distance | Maximum efficiency | Advantage | Disadvantage |
|---|---|---|---|---|
| Laser | Kilometer-level | ~15% | have the largest distance and a good directionality | has high requirements of optical alignment and is greatly affected by weather |
| Microwave | Meter level | ~40% | Beamforming is flexible and has good environmental adaptability | The rectification efficiency fluctuates with the frequency band and power |
| Ultrasonic | 0.8 m | 9% | It can operate in underwater and enclosed environments and integrates communication functions | The distance attenuation is fast and the efficiency is greatly affected by the medium |
| type | Effective distance | Maximum efficiency | Advantage | Disadvantage |

From the comparison, it can be seen that the laser type is suitable for long-distance point-to-point high-power transmission, the microwave type is suitable for flexible energy supply over medium and short distances, and the ultrasonic type has irreplaceable advantages in special environments.

## 4. Design Concept of Microwave-Ultrasonic Hybrid Wireless Charging System

To enhance the power supply stability and adaptability of radiant wireless charging technology in complex environments, this section proposes a microwave-ultrasonic hybrid wireless energy transmission architecture. The feasibility of this system is based on the similarity in architecture between microwave wireless charging systems and ultrasonic wireless charging systems. This system combines the high directionality and high efficiency advantages of microwave wireless energy in long-distance and wide-range power supply, as well as the low attenuation, good penetration and high safety characteristics of ultrasonic waves in underwater or enclosed Spaces [8], to achieve energy transmission across media and in multiple scenarios.

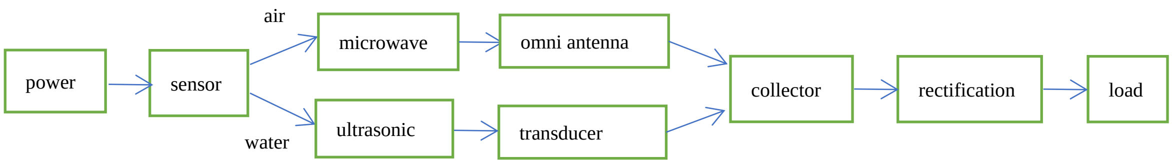


**Fig. 4** The basic structure of the hybrid system

As shown in Figure 4, the system consists of two parallel links. Microwave links are used to achieve high-efficiency directional transmission over tens to hundreds of meters in the air and have certain dynamic tracking capabilities [9]; Ultrasonic links can be used to provide stable energy in special environments such as liquid media and metal casings, and can further enhance data transmission capabilities while achieving both energy supply and communication functions [8]. During operation, the energy management module acquires the medium conditions through sensors and dynamically allocates power between the two links to achieve link complementarity and optimal efficiency.

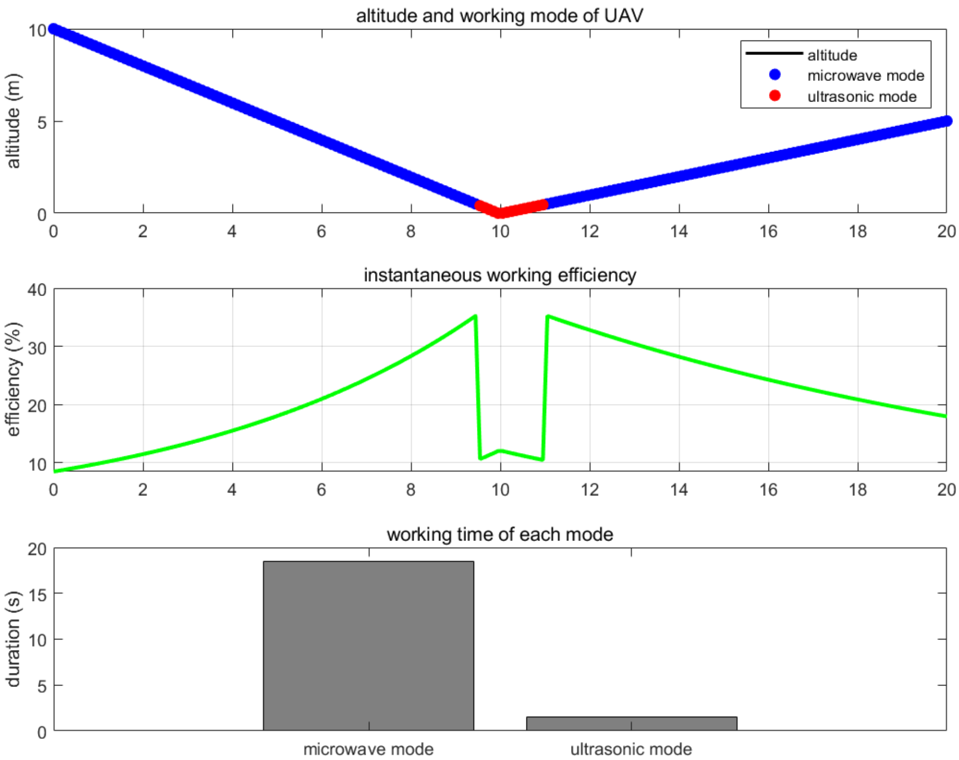


**Fig. 5** MATLAB simulation results of hybrid system efficiency

To illustrate the specific application scenarios of this hybrid system, this paper envisions a situation where the unmanned aerial vehicle is in a seawater environment when it is below 0.5 meters above the ground and in an air environment when it is above 0.5 meters. The simulation results in this case are shown in Figure 5. The mathematical simulation results show that in the free-space scenario, the microwave link is the main power supply channel. In high-humidity, liquid or metal barrier environments, the ultrasonic link will take over the power supply task. Compared with the single energy supply system of microwave or ultrasonic waves, this system will improve the overall utilization rate of energy.

The potential application scenarios of this hybrid architecture are very extensive. In multi-media continuous operations involving air, water and land, such as the coordinated cruise operation of unmanned aerial vehicles (UAVs) and unmanned vessels, the hybrid energy supply system can obtain long-distance energy supply through microwaves when the UAV is flying in the air, and switch to ultrasonic links when the unmanned vessel dives or approaches water bodies, achieving stable energy supply across environments. In the field of Marine exploration, underwater sensor networks often need to be distributed in deep-sea environments for a long time. A traditional wired power supply is difficult to achieve. However, hybrid systems can not only use microwaves for centralized energy replenishment on the water surface but also supply power to equipment through ultrasonic waves penetrating seawater or bulkheads, thereby significantly enhancing the system's endurance and deployment flexibility. In extreme environments such as disaster relief, for instance, building collapses, mine accidents, or flood-stricken areas, rescue robots can obtain electrical energy by penetrating obstacles with ultrasonic waves, while aerial base station drones can use microwaves for long-distance energy transmission, thus ensuring the long-term operation of rescue equipment and reducing the risk of rescue interruption caused by insufficient power.

Based on this assumption, future research can be further expanded. For instance, to build a more complex composite energy supply system, a laser link can be added to the existing microwave-ultrasonic architecture to form a three-mode energy supply, achieving full coverage from the air to underwater. By integrating high-efficiency power drive circuits with miniaturized transducer arrays [10], the integration and engineering availability of the system are further enhanced. Meanwhile, explore the use of neural network algorithms to intelligently control beam pointing and power distribution, thereby achieving dynamic optimization of energy in multiple terminals and environments. Through these application expansions and technological optimizations, this hybrid architecture is expected to form a truly cross-media and cross-scenario wireless energy network in the future.

## 5. Conclusion

This article systematically reviews the principles and performance characteristics of three radiative wireless charging technologies: laser, microwave and ultrasonic. It points out that the laser solution is suitable for long-distance high-power point-to-point power supply, the microwave solution takes into account flexible regulation and medium and long-distance coverage, and the ultrasonic solution has unique advantages in special media and enclosed Spaces. Comparative analysis shows that different technologies have their own strengths in terms of efficiency, transmission distance and environmental adaptability. Meanwhile, this paper also presents feasible application scenarios for hybrid radiation wireless charging, indicating that it has high application value in the future. Future related research may further expand in areas such as dynamically optimizing beam direction and power distribution through machine learning, developing new and efficient receiving materials, and integrating multiple transmission methods of light, electricity, and sound on the same platform to achieve environmental adaptation and self-switching.

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