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Long-Range Wireless Microwave Power Transmission: A Review of Recent Progress

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Abstract- **The concept of long-range microwave power transmission (MPT) has been driven by the desire to remotely power satellites, drones, or some mobile facilities. The advantage of long-range MPT is power transmission over a long distance without the need to deploy a wired power network. However, the overall efficiency, robustness, directional radiation (DR), etc., are still issues that limit the application and further research. In this framework, the key challenges in designing transmitters, directional radiation and receivers that can guarantee high efficiency and precise tracking for long-range MPT have been acknowledged. Owing to the complexity, the design of MPT systems remains an open research question. Focusing on the existing constraints, this paper not only elaborates on current major research topics and discusses the development trends but also reviews the design approaches proposed in the state of the art for long-range MPT. This power transmission mechanism shows essential meanings of application in daily life, and the current research status and development prospects for MPT are also presented in this paper.**

I. Introduction

As the most widely used power transmission method, the wired power transmission strategy has undoubtedly contributed to the development of the electrical age. Here, a large energy source provides power for various industries through transmission cables. However, with the development of science and technology and the improvement of human living standards, the problems and limitations of traditional wired power transmission strategies have become increasingly apparent: poor flexibility, incompatibility in certain circumstances (such as implanted medical equipment), and safety hazards in some occasions. In order to eliminate the necessity of a physical connection during the charging process, people's demand for wireless power transmission (WPT) is becoming stronger and more urgent [1][2][3].

The development of WPT is advancing in two major directions: One is near-field techniques such as capacitive power transmission (CPT) [4] and inductive power transfer (IPT) [5][6]. The other is far-field techniques, such as laser power transmission (LPT) [7] and microwave power transmission (MPT) [3]. The near-field technique utilizes the inductive coupling effectiveness of nonradiative electromagnetic fields, including inductive and capacitive mechanisms. By utilizing near-field techniques, battery-powered devices can harness wireless power from an electromagnetic field in air and then charge their batteries cordlessly even in the moving state [8]. Far-field techniques such as LPT and MPT are usually used in long-range power transmission scenarios.

Table I
Comparison of microwave and laser power transmission used in SPS

	Microwave	Laser
Frequency (wave length)	5.8GHz	1.06um
DC-RF efficiency	80% (expected)	60% (expected)
Atmospheric transmission	97%	80%
RF-DC efficiency	80% (expected)	60% (expected)

With the development of society, one of the major global issues is the energy problem combined with a shortage of natural energy resources and increasing atmospheric concentrations of CO_2. A solar power satellite (SPS) that converts the sun's energy into electricity in space and transmits it to the ground is one of the potential candidates and probably the realistic solution. The SPS was first proposed by the National Aeronautics and Space Administration (NASA) in the 1970s [9]. In long-range power transmission, several strategies could probably be used in SPS. The Japanese Aerospace Exploration Agency (JAXA) has performed relevant research to implement practical methods[10]. In the MPT system, the efficiency of both the transmitter and receiver is generally higher than that of LPT. Moreover, the attenuation through the atmosphere in MPT is also lower than that in LPT. The comparison between microwaves and lasers is presented in Table I. In this paper, the systematic review of MPT is the major emphasis.

In the 1950s, a number of developments occurred that revealed that MPT transmission efficiency could approach 100% [3]. Calculations and experimental results gathered by Goubau and Schwering demonstrated that the transmission efficiency in free space could reach 100% by a beam waveguide of lenses and/or reflecting mirrors[11]. The U.S. Air Force/Raytheon Company proposed a helicopter positioned at 50000 ft in a region above the jet stream in the 1960s. The helicopter needed to be powered by a power generator having 400 kW output of power at 3 GHz with an efficiency of over 80%. This high-power and high-efficiency power generator was developed by

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Table II
Summary of main programs of MPT system

Literature	Operation Frequency (GHz)	Transmission Distance (m)	Power Level (W)	Efficiency
[13]	2.45	15.24	-	-
[15]	2.446	1.7	495 (Receiver DC Power)	54.18% (Overall efficiency)
[16]	2.388	1600	30000 (Transmitter RF Power)	-
[17]	2.45	150	150 (Receiver DC Power)	-
[19]	2.45	-	166 (Receiver Power)	-
[20]	5.8	10	-	41.85% (Transfer efficiency)
[21]	0.915	15	10 (Receiver DC Power)	≤10% (Overall efficiency)
[26]	5.8	2	6.4	1.3% (Overall efficiency)
[27]	5.8	54	1800	35% (DC-RF efficiency)
[28]	5.8	0.4	100×10^{-3}	24.3% (Transfer efficiency)
[29]	2.45	1	-	-
[30]	10	4	3.44	55% (Antenna efficiency)

W. C Brown, who is widely regarded as the principal pioneer of practical MPT [12]. This paper mainly reviews the evolvement of MPT techniques in recent years and will not mention a lot of milestones in the historical development of the MPT system. In 1974, with funding from NASA, W.C. Brown and his Raytheon colleagues improved the overall efficiency of the MPT system [14]. The overall DC-DC efficiency was 54%, the operation frequency was 2.446 GHz, and the output DC power level was 495 W [15]. The overall efficiency reached then has not been surpassed even in recent years.

Decades later, the center research of MPT shifted to Japan, Europe and Canada. In Japan, many experiments have been performed during the past decades. Because of adequate funding, a couple of these programs have been involved in space experiments. In 1992, the Microwave Lifted Airplane Experiment (MILAX) project was the first to use an electronically scanned phased array to keep a 2.41 GHz microwave power beam on a moving target [18]. In the last decade, numerous papers have been written about MPT systems or component architectures. In 2008, an experiment carried out by John Mankins with researchers at Texas A&M University and the University of Kobe Japan transmitted power from a Maui-based array to the large island of Hawaii over a distance of 148 km [3]. However, the efficiency was less than 1%. In China, Sichuan University has built a platform to verify MPT theories. The operation frequency was 5.8 GHz, and the transmission distance can reach hundreds of meters [20]. Directional radiation is also an essential application in MPT systems; as described in [21], directional radiation could be achieved by using a maximum power transmission strategy. In addition to the abovementioned demonstrations of MPT systems, some other validations are summarized in Table II.

Table III
Antenna size and attenuation comparison

Frequency	Ref	Antenna type	Antenna Size(mm)	Atmospheric attenuation	Ionospheric attenuation
2.4GHz	[31]	FSS patch antenna	90×90	≈2%	<1%
	[70]	Horn antenna	192×142		
	[32]	Microstrip patch antenna	40×40		
5.8GHz	[33]	Dielectric resonator antenna	45×45	≈8%	<1%
	[34]	Horn Antenna	76×23.9		
	[35]	Microstrip patch antenna	30×30		

Based on the review of the historical achievement, the frequency selection in MPT system is basically 2.4GHz or 5.8GHz. Both two frequency bands belong to ISM (Industrial Scientific Medical) band which means could be used as fundamental research and would not interference the normal communication. Table III shows the comparison of antenna size and attenuation between 2.4GHz and 5.8GHz. From comparison, the atmospheric absorption has different effect on the attenuation of the transmitted power [22][10]. At 2.4GHz frequency band, there is lower attenuation when propagating through the atmosphere. The ionospheric attenuation could be negligible when the frequency is 2.4GHz and 5.8GHz [22].

Besides, size of antenna is also an important factor to measure the entire MPT system. In general, the higher frequencies, the scale of the transmitting/receiving antenna can be smaller. Table III shows that the horn antenna used in 2.4GHz is 60%-80% larger than 5.8GHz. As the antenna design and energy harvesting techniques develop in depth, the antenna design incorporates material science, microwave engineering and other technology field. For instance, the use of frequency selective surface (FSS) technique could change the size of antenna more flexible. In wearable applications, due to the demand of portability, higher operating frequencies in MPT system have advantages [23][24]. In the application of long-distance charging for base stations, if the demand for volume or electromagnetic compatibility is not strong, 2.4GHz has a higher power density and maybe a better choice [25].Therefore, certain tradeoffs need to be made when selecting frequency bands under different application scenarios.

In recent years, many studies based on component architectures have been presented, and the basic principles of each component are elaborated in Section II. Then, in Section III, this paper systematically summarizes the major technical challenges. Section IV discusses the research issues and future development of MPT systems. Finally, Section V draws a brief conclusion about prospects for these systems.

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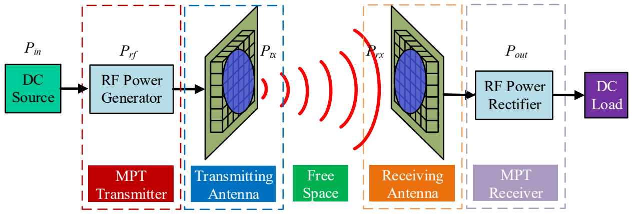

Fig. 1 MPT system architecture

II. Basic Principles of The MPT System

A. System architectures of the MPT transmitter

Fig. 1 schematically shows a diagram of the MPT system [36]. In this system, a DC source with power P_{in} is fed to an MPT transmitter. The transmitter converts DC input power to RF output power that provides excitation for the transmitting antenna. This antenna, usually a phased array antenna, shapes the RF power to an intensified microwave beam and radiates it to free space. The receiving antenna captures the radiated beam and transfers the energy to a rectifier. The receiver, essentially an RF rectifier [37], converts the received RF power to a DC output P_{out}. Usually, the receiving antenna and rectifier are combined as a whole part named the rectenna, which is widely used in MPT systems [38].

Transmitters of MPT systems usually have one of two kinds of architectures: a lumped type or a distributed type. Fig. 2 shows a schematic diagram of the lumped architecture. The architecture of the lumped type usually consists of a magnetron or travelling wave tube (TWT), which has the advantages of high power and high efficiency [39][40]. In recent years, the magnetrons output power could reach to 3.5kW and control the four-way injected signals to lock the slave magnetrons [41]. Moreover, in [42], when the magnetron utilizing a frequency-searching injection-locking technique, the efficiency could research to 94.6%. As discussed in [43], the power-to-weight ratio is also worth considering when comparing the different architectures of MPT transmitters. The higher the efficiency, the less launching weight and size are required. In long-range high power application scenarios, the lumped type, which consists of a magnetron or TWT, has been commonly used in recent years.

To achieve the directional radiation (DR) function of microwave power, phase shifters are usually cascaded after the power generator [44], which can control the beam direction. However, whether using a digital phase shifter or an ordinary phase shifter, the cost and precision of the phase shifters are the major issues. Because high precision phase shifters are expensive, therefore, the lumped architecture of the MPT transmitter is usually set up on a mechanical turntable to achieve microwave power directional radiation. The strategy of directional radiation that uses a mechanical turntable brings the issues of large volume and heavy weight. Therefore, in order to decrease the size of the MPT volume and cost, a distributed type of MPT system has been researched in recent years.

Fig. 3 shows a schematic diagram of the distributed type of MPT transmitter. The semiconductor PA is fed by an RF signal and controlled by a digital signal processor (DSP) to realize

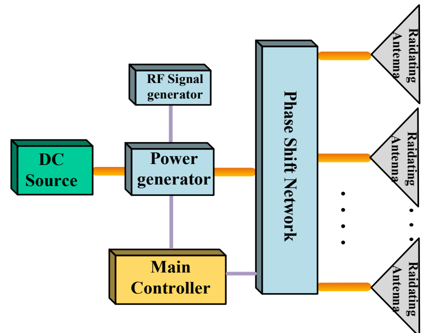

Fig. 2 Lumped type of MPT transmitter

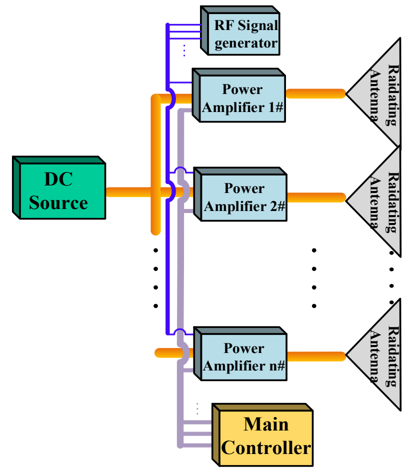

Fig. 3 Distributed type of MPT transmitter

phase and amplitude control. The literature [45] shows that the efficiency of the PA can reach 70% at 5.8 GHz. With the development of novel devices, the distributed type will have more applications in the future. In the architecture of the distributed type of MPT, directional radiation based on phased array antenna theory can be achieved without the mechanical turntable. Moreover, based on the distributed architecture, beam control technologies have evolved rapidly. In section III, the specific techniques will be elaborated in detail. In this structure, the PA's efficiency and design of phase and amplitude control are the focus of current research.

B. Available types of power amplifiers

Gallium nitride (GaN) is one of the most significant elements to achieve effective use of MPT systems. In the transmitter, usually in the RF power amplification stage, PA efficiency is essential. Currently, solid-state power amplifiers

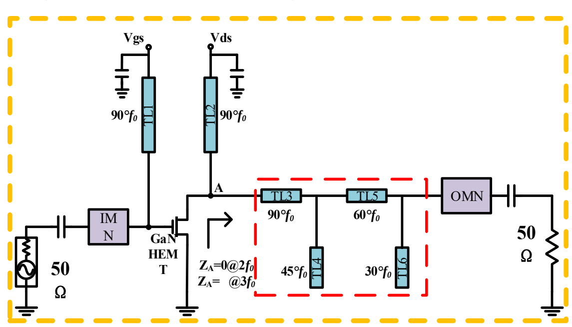

Fig. 4 Circuit topology for class-F

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often use GaN devices. This is because GaN has advantages such as high efficiency, high breakdown voltage, and harsh environment robustness, and it is expected to meet the requirements for low noise amplifier (LNA)[46]. Using GaN devices, the flexibilities for future missions in terms of the size, weight, and power consumption, etc. will be improved significantly. Many kinds of topologies using GaN devices, such as the class-E, class-F, class-F^{-1} or reconfigurable structures, have been proposed to achieve high efficiency [47].

In the class-E structure, a transistor acts as a switch. The voltage of the class-E amplifier is generated by charging and discharging an output capacitor in parallel with this switch. Since this amplifier tunes all harmonic components using the *LC* resonator, it delivers the highest efficiency among the proposed amplifiers. However, the charging step of the capacitor cannot be abrupt. Above the theoretical maximum frequency, the capacitor cannot discharge fast enough to support the ideal waveform[47][48]. In the power electronics area, class-E is usually used in very high frequency circuits. The converter provides over 500 W of RF power at a drain efficiency above 92% [49]; as reported previously [50] the efficiency can reach 77%. However, the operation frequencies are 30 MHz and 100 MHz. Compared with the frequency of the microwave level, there is still a gap. Therefore, the development of GaN devices could also promote the evolution of power electronics.

In the microwave frequency band, because of the nonlinearity of devices, the output power contains very large harmonics; moreover, the harmonics cause the power to reflect and may decrease the efficiency. Harmonic control circuits have been proposed as high-efficiency PA circuits. Fig. 4 shows the schematic diagram of the class-F power amplifier.

The class-F mode is one of the most cited highly efficient PAs [51]. Following the widely accepted definition, its design consists of terminating the device output with open-circuit terminations at odd harmonic frequencies of the fundamental component and short-circuit at even harmonics. As a result, a squared output voltage waveform is generated from the imposed half-sinusoid output current waveform. In recent years, inverse class-F (class-F^{-1}) has been introduced and researched. In fact, compared with class-F, the current and voltage output waveforms for inverse class-F are ideally interchanged. Thus, for optimum operation, the output harmonic loads have to present zero impedance at odd harmonics of the fundamental frequency and open circuits at even harmonics [52]. Among the modes mentioned above, another new PA structure is class-J. This novel structure achieves the same output power and drain efficiency as class-B counterparts over a broad bandwidth [53]. In addition, class-J mode also features good linearity and backoff efficiency, which makes it a very promising option for broadband PAs employed in WiMAX and 5G systems [54].

C. Power transmission in free space

Currently, there are various strategies of directional radiation in free space. The strategy of the mechanical turntable is widely used in MPT systems as the most intuitive method. However, because of the turntable's heavy weight, large volume and poor precision of directional radiation, the strategy of phased array antenna, which is widely used in radar systems, has become the research focus in MPT systems. Fig. 5 shows the principles of the traditional *M*N* phased array antenna. Each radiating element (m, n) is located at (x_m, y_n):

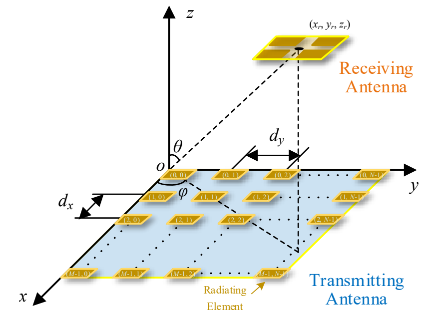

Fig. 5 The diagram of phased array antenna

$$\begin{cases} x_m = md_x & m = 0,\dots,M-1 \\ y_n = nd_y & n = 0,\dots,N-1 \end{cases} \quad (1)$$

where d_x and d_y are respectively the distances between the elements along the x-axis and y-axis.

According to the theory of a classic phased array antenna, to steer the beam toward direction (φ, θ), the excitation for each element should be:

$$f_{mn}(u,v) = w_{mn} e^{jk(ux_m + vy_n)} \quad (2)$$

where w_{mn} is the normalized weight for element (m, n) and

$$\begin{cases} k = 2\pi/\lambda \\ u = \sin(\theta)\cos(\varphi) \\ v = \sin(\theta)\sin(\varphi) \end{cases} \quad (3)$$

where λ is the wavelength, k is the wavenumber, and u and v are defined in a spherical coordinate system as usual.

For phased array antennas, amplitude-controlled excitations make it possible to achieve sidelobe suppression and power-efficiency optimization, which visually leads to a more intensified transmitting beam [55]. Additionally, phase-controlled excitations yield a steering phenomenon, which visually changes the direction of the main lobe and forces it to radiate to an envisaged collecting area. Based on this principle, beam steering could also be achieved by rotating the rotatable lenses [56].Moreover, a multi-objective optimization model is established in [57] to maximize the beam collection efficiency.

As stated above, microwave power transmission in free space should be able to a) steer the beam toward the receiver direction

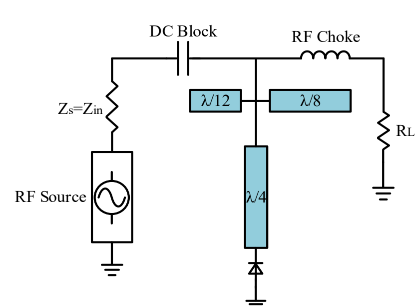

Fig. 6 Ideal class-F rectifier topology

and b) shape the radiated beam through suitable weighting strategies so that the power sent toward the receiver is maximized [58]. Specific technical details are shown in section III.

D. Available types of rectifier

Several types of topologies are employed to realize the rectifiers that are used in the MPT receiver, for instance, diodes in series, diodes in parallel or diodes in the voltage doubler. Furthermore, different kinds of topologies and analytical models have been proposed [59][60]. In traditional strategies, rectifiers are usually optimized for specific operating conditions, such as a fixed operation frequency and constant input power. However, the available electromagnetic power is generally not constant, and the load varies in real time. Under the microwave frequency band, variations in the power, frequency, and load lead to impedance variation since the rectifying device is nonlinear. The impedance mismatch degrades the rectifier performance; thus, the efficiency of the MPT receiver is decreased [61].

Regarding low power rectification, energy harvesting has drawn great attention recently, especially techniques based on the microwave frequency band, which can provide a flexible and reliable energy flow without any intermittence [62]. RF energy harvesting usually used in the charging scenarios of sensor node and wearable device, for detecting changes of environment, moisture or pressure of equipment. Benefited from increasingly low power level of consumption, wearable devices are widely used in daily life. However, RF energy harvesting is not easy to implement effectively. The power density of ambient RF energy is very low and probably leads to a low level of collected RF power. The low input RF power will cause a poor RF-to-DC conversion efficiency, which becomes the major obstacle to the RF energy harvesting[63][64]. Since the rectifying devices which use Schottky diodes, transistors, and CMOS schemes, the power capacity is quite low, therefore, the structure of rectenna which usually used in RF energy harvesting is arranged in series. In the scenarios of medium power level or high power level, different structures or inverse PA topologies are worth continuing research.

Active rectification is also a recent research focus. The literature [65] includes the implementation of a class-E RF rectifier based on reconfiguring a class-E power amplifier circuit. That RF rectifier delivered 50 mW of dc power with an efficiency of 83% at a frequency of 900 MHz. Literature [64] used the theory of time-reversal duality to show that a rectifier could be constructed from an amplifier by reversing the power flow in the amplifier circuit from the load to the DC supply. Other researchers [66][67] have continued to use the concept of time-reversal duality to explore the implementation of RF rectifier topologies and aim to improve the conversion efficiency and power level of high-frequency applications. Fig. 6 shows the ideal class-F rectifier topology. This rectifier uses an ideal RF choke, ideal DC block, and lossless transmission line, besides the source impedance is set to be conjugate matched to the rectifier input impedance at various input power levels [68].

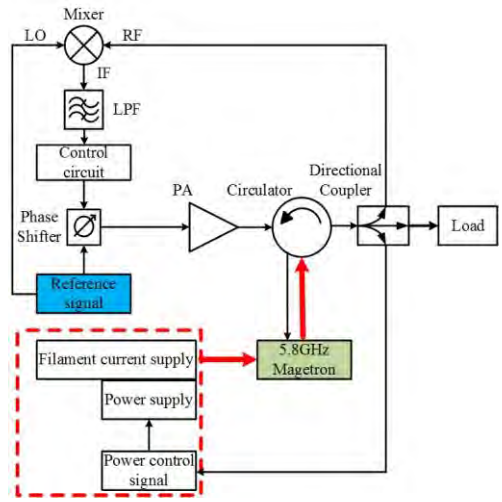

Fig. 7 Schematic of phase-controlled magnetron

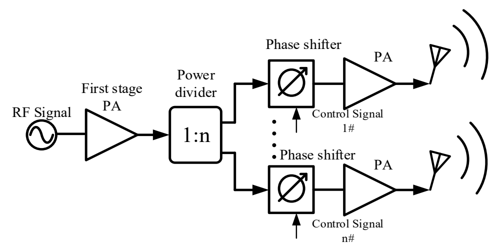

Fig. 8 Conventional structure of phase control in MPT transmitter

III. Specific Techniques in MPT System

As mentioned in the previous section, the capabilities of amplitude and phase control of MPT transmitter, beam directing radiation, and the rectification efficiency impose critical effect on the performance of the MPT system. Therefore, the optimization of control strategies and efficiency improvement are strongly required.

In this section, we summarize the methods that can be used to improve the overall efficiency and achieve directional function. Firstly, in order to make better use of the transmitter, a variety of amplitude and phase control methods are described. Secondly, several beam steering strategies are introduced. Finally, based on the efficiency improvement, multiple structures of MPT receiver and rectenna are presented.

A. Control strategies optimization for MPT transmitter

In MPT systems, directional radiation is an essential application; although some types of transmitters that use magnetrons, TWT, etc. can achieve high power level, phase and amplitude control remains a research problem to be solved. The compatibility of high-efficiency beam forming in MPT has been researched. Researchers at Kyoto University proposed and developed a phased array using magnetrons. One example is a phase-controlled magnetron (PCM) with an injection locking technique and phase locked loop (PLL) feedback to the magnetron voltage source [69]. This structure could achieve more than 4 kW microwave power and had a DC-RF efficiency higher than 70.5%.

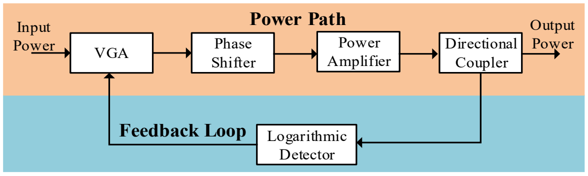

Fig. 9 Schematic of AGC control

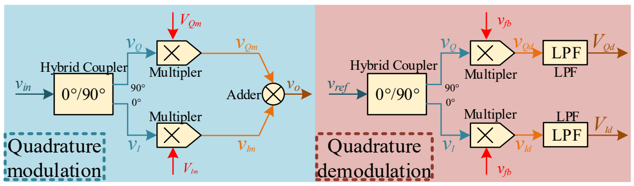

Fig. 10 Schematic of quadrature modulation and demodulation

In 2017, researchers at Kyoto University optimized the control strategy. They controlled the phase of 5.8 GHz magnetron output by a phase shifter without the anode current control PLL method. The proposed structure is shown in Fig. 7. From this structure, the output phase of the magnetron from the directional coupler is compared with the reference signal phase in the double balanced mixer. The phase difference signal from the mixer is input to the control circuit to control the phase shifter. Then, the phase shifter changes the reference signal phase to be injected into the magnetron. By this PLL, the phase difference gradually converges to zero. By another loop, the output signal is compared with the power setting signal and then feeds back on the high-voltage power supply. This approach can change the anode current of the magnetron to control the magnetron output power [44]. However, the transmitter's volume and weight were quite large in the literature mentioned above, and its weight could reach 45 kg [70]. Thus, more development is required before this approach is widely used. The use of solid-state power amplifiers or semiconductor technology to realize directional radiation will be the focus of future development.

In recent decades, directional radiation techniques widely used in the radar system or communication field have been borrowed and applied in MPT systems. As mentioned above, phased array antennas are one of the most widely used techniques for directional radiation applications since the transmitter does not need to move in real time. A phased array antenna requires the transmitter to have the ability to change the phase differences between each antenna element. The conventional strategy is to use a phase shifter to change the phase differences between each antenna element. However, the insertion loss of the phase shifter can result in inconsistency of the entire transmitter [71]. Fig. 8 shows the structure of the conventional phase shifter method.

To compensate for the insertion loss of the phase shifter and improve the consistency of each module in the transmitter, various schemes have been proposed to elevate the situation. In [72][73], an automatic gain control (AGC) loop was presented to compensate for the loss caused by the modules in the transmitter. Usually, an AGC [74] amplifier is used to achieve an RF signal with constant amplitude for the succeeding PA and inconsistent recovery circuit. A variable gain amplifier chip is usually used in the AGC loop. This kind of control method has been used for decades and can be highly integrated in chips. Fig. 9 shows the diagram of the AGC loop.

Another study [71] presents the phase and amplitude control of the transmitter, which uses quadrature modulation and demodulation. The architecture diagram is shown in Fig. 10. Quadrature modulation and demodulation are also respectively named I-Q modulation and demodulation. They are widely used in communication areas. In these techniques, any sinusoidal signal can be separated into two quadrature sinusoidal signals, namely, the in-direction signal (v_I) and the quadrature signal (v_Q):

$$\begin{aligned} v_{in} &= \sqrt{2}V_{in}\cos(\omega t - \frac{\pi}{4}) = v_Q + v_I \\ &= V_{in}\cos(\omega t) + V_{in}\sin(\omega t) \end{aligned} \tag{4}$$

In equation (4), ω is the angular frequency in rad/s, and V_{in} is the amplitude of v_{in}. We multiply v_I and v_Q with different DC values (V_{IM} and $V_{QM,}$ respectively) and add them together; the output signal can be represented as:

$$\begin{aligned} v_o &= v_{Qm} + v_{Im} = V_{Qm}v_Q + V_{Im}v_I \\ &= \sqrt{2}V_{in}\sqrt{{V_{Qm}}^2 + {V_{Im}}^2}\cos(\omega t + \varphi) \end{aligned} \tag{5}$$

Quadrature demodulation, the inverse process to quadrature modulation, extracts both the in-direction signal (v_{Id}) and quadrature signal (v_{Qd}) modulated in the original input. As shown in Fig. 10, the reference signal (v_{ref}) is sent to a hybrid coupler, giving one in-phase reference signal v_I' and quadrature reference signal v_Q'. The two signals both multiply with the feedback signal (v_{fb}) to provide two baseband signals:

$$\begin{aligned} v_{Qd} &= V_{fb}V_{ref}[\sin(\varphi_{fb} - \varphi_{ref}) + \sin(2\omega t + \varphi_{fb} + \varphi_{ref})]/2 \\ v_{Id} &= V_{fb}V_{ref}[\cos(\varphi_{fb} - \varphi_{ref}) + \cos(2\omega t + \varphi_{fb} + \varphi_{ref})]/2 \end{aligned} \tag{6}$$

In equation (6), V_{fb} and V_{ref} are the amplitudes of v_{fb} and v_{ref}, respectively, while φ_{fb} and φ_{ref} are the initial phases of the two input signals. Based on the equations above, the phase and amplitude can be fully controlled by the digital controller, and this method not only reduces the size of the transmitter but also is a cost-effective way to implement directional radiation in MPT.

Combined with phased array antenna theory, directional radiation can realize functions such as multitarget emission and beam forming, which has great flexibility and high research value. In this paper, the MPT transmitter based on phased control is elaborated. Beyond phase control, the amplitude adjustment can also achieve beam steering and realize the improvement of transmission efficiency. Moreover, frequency diverse arrays (FDAs) [75], as another research focus, may also be applied in MPT systems.

B. Beam steering strategies for directional radiation in MPT

MPT systems operating over a long distance require the transmission of RF electromagnetic beams from the generating point to the faraway receiver. Consequently, the fundamentals of directional radiation techniques are closely related to those of wireless communication and radar systems [76][77]. However, owing to the specific objectives of MPT applications, the long-range viability of such systems requires addressing

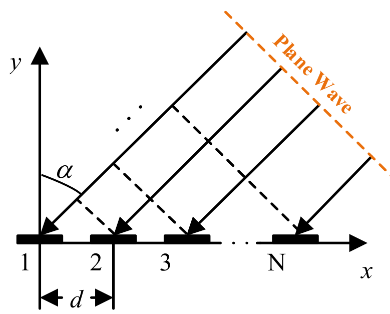

Fig. 11 Conventional phased array antenna

their constraints and goals through a new perspective in terms of theoretical tools and design approaches. Beam steering strategies contain two key components that enable electromagnetic power transfer, namely, the transmitting antenna and the beam controlling technology.

As stated above, the fundamental requirement of the transmitting antenna is its ability to maximize the radiating efficiency. The antenna design is not the major concern in this paper. Beam steering strategies that can control RF power toward the collecting region have received much research interest.

Because of its importance on the efficiency of power transmission in the free space, the MPT beam steering problems has been received much attention. More recently, several kinds of methodologies have been proposed to obtain the beam steering strategies for moving targets in terms of power signal feedback, pilot signal tracking, et.al.

1) Directing radiation using the maximum received power

Based on antenna theory, the free space can be separated into two major regions, near-field and far-field, and techniques that are based on phased array antennas, usually operate in the far-field. In the far-field, the electromagnetic wave has become a plane wave, so that the phase difference between each antenna element is the same. A schematic of the conventional phased array antenna is shown in Fig. 11.

A phased array antenna can provide high gain and electronic steering, achieve dynamic beam forming and realize directional radiation in MPT systems or satellite communication and other areas. However, the deterioration of the phases and amplitude may harm the performance. Many methods have been proposed to measure the errors of the elements in order to achieve precise directional radiation, including the rotating-element electric field vector (REV) method, near-field probe, mutual coupling-based measurements and so on [78]. Novel directional radiation methodologies have been developed based on phased array calibration methods.

When the MPT system radiates power directionally, a slight angle error will cause beam pointing deviation. In actual calibration process, limited by the bits and the characteristic of phase shifter, the phase-shifting error is one of the main error [79]. To avoid error which is brought by phase shifters, and achieve accurate microwave power transmission, the strategy of iterative superposition is proposed in literature [21]. Iterative superposition, which is based on REV calibration in a phased array antenna, can realize directional radiation through maximum power reception. E_i, i=1, 2, ..., (M*N), is the electric field vector in the rectenna's position, as generated by radiating elements. If ideally directional radiation is intended, all electric field vectors should be arranged as shown in Fig. 12 (a). All these vectors are in the same direction so that they can form the maximum electric field. Due to the practical impact in free space, a practical electric field vector arrangement using iterative superposition is as shown in Fig. 12 (b). As illustrated in Fig. 12 (c), the following algorithm is intended to correct all these direction errors and leads to a new arrangement close to the ideal one. The iterative process is based on the following steps [21]:

a) Turn off all excitations denoted as RF_{out_i}, i=1, 2, ..., M*N; Initialize an array δ_{Gopt} to store the phase setting (all elements set to 0°). Turn on the first excitation with maximum output and phase of 0°. Let i=2;

b) For RF_{out_i}, maximize its amplitude. Change its phase from 0°;

c) Let i=i+1. If i>M*N, go to d). Otherwise, go back to b);

d) Iteration finished. Continue radiating using the phase setting given by δ_{Gopt}.

When conducted appropriately, iterative superposition achieves the appropriate directional radiation performance, as this algorithm always yields a maximum electric field that leads to a maximum power correspondingly. However, a large number of iterations are required with the algorithm, which consumes a longer running time than conventional phased array antennas.

Owing to the main limitations of current directional radiation methods, that is, the costs, volume and weight, and complexity, most of the present efforts are aimed at the following objectives [58]:

a) Increasing the accuracy and robustness of directional radiation techniques;

b) Reducing the operation complexity of the feeding network;

c) Decreasing the volume and weight of the MPT transmitter;

d)Shrinking the time consumption when performing directional radiation.

Using Iterative superposition method to realize directional radiation could make the MPT receiver achieve more power. However, the response speed is not fast, when power transfer to fast moving target, it will cause deviation of beam direction. To realize beam tracking of fast moving target, the use of pilot signals is an interesting method.

2) Directing radiation using pilot signals

Such a time-consuming problem can be resolved by the strategy of directional-of-arrival (DoA) estimation with pilot signals [80][82]. The beam steering technology is called

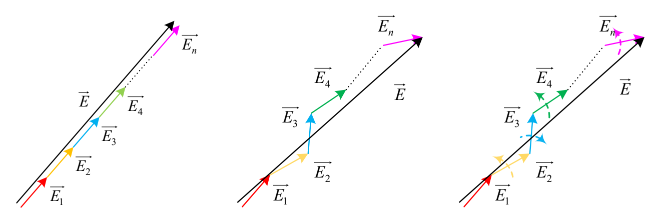

Fig. 12. Iterative superposition of directional radiation

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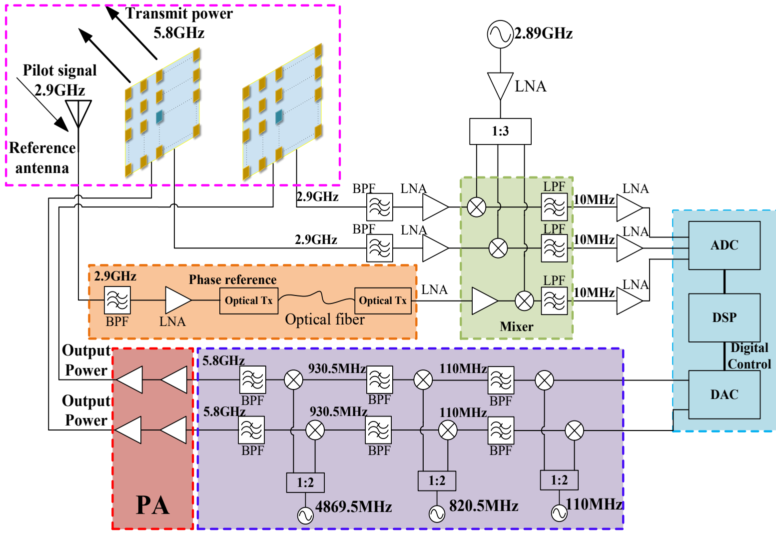

Fig. 13 Schematic of retro-directive strategy in 5.8GHz MPT system

retrodirective and is based on the theory of the phase conjugation scheme [81] according to the following steps [82]:

a) Capture the phase of the pilot signal φ_n;

b) For each antenna element, compare φ_n with the onboard reference phase $\hat{\varphi}$, and capture the phase difference $\Delta\varphi_n = \varphi_n - \hat{\varphi}$;

c) Feed the n_{th} element with the phase $\gamma_n = -\Delta\varphi_n$ (conjugation) so that the beam wave emits toward the receiver.

Retrodirective beam steering technology has the advantage of enabling automatic following procedures with the assistance of a pilot signal. Although an additional pilot signal transmitting device is required in the receiver, the retrodirective methodology shrinks the running time required to follow the moving target.

Approaches that are able to achieve enhanced performance with respect to classical retrodirective beam steering technology have been recently investigated [83][84]. The method of position and angle correction (PAC) has been introduced with the aim of achieving optimum beam steering in the precise position. Moreover, the PAC algorithm requires the pilot signal sent by the receiver to be processed so that its phase is measured on each antenna element [82]. A prototype of retrodirective system based on the PAC algorithm has been demonstrated to yield an error ≤1° in the phase compensation when using 2.94 GHz pilot signal [82][85].

Fig. 13 illustrates the retrodirective system in detail. Two array antennas are used to demonstrate the feasibility of the system. The pilot signal of 2.9 GHz is received by subantennas that are located at the center of each array antenna. The signal is filtered by a low pass filter (LPF) and then mixed with a signal from a local oscillator (LO) to produce an intermediate frequency (IF) signal that is fed to an analog-to-digital converter (ADC). In a digital control unit, an algorithm based on phase conjugation theory inverts the phase difference between the phase received by the array element and the reference phase.

The reference phase after filtering and amplification transmits through the fiber system, achieving anti-interference capability before being down-converted to IF and digitized at the ADC. A digital signal processor (DSP) produces digital output signals with phase information for the separate subarrays. Then, a digital-to-analog converter (DAC) generates analog IF signals for each transmitting antenna element. These signals are filtered and upconverted in three stages to produce a 5.8 GHz transmission signal. The phase of each signal is controlled at the IF frequency so that phase conjugation is maintained at 5.8 GHz [81].

Furthermore, implementing retrodirective from hardware by employing Van Atta arrays [86], and the switched beam antenna layouts [87] which could be used in 5G mobile are also worth noting. To further improve the accuracy and dynamic adjustment of directional radiation, array calibration approaches targeted at MPT have been proposed as well. A significant improvement in terms of steering accuracy and beam control over the array antenna has been achieved [88]. In MPT system, the higher gain of antenna array means more concentrated power of beam and better capability of beam direction radiation. Existing research usually focus on single target power transfer, in the future research of multi-targets and real-time power transmission, beam steering technology will be an essential part.

C. Efficiency optimization for the MPT receiver

The overall efficiency of the MPT system heavily depends on the RF-DC conversion efficiency of the rectifier. The structures of the MPT receiver, topologies of the rectification circuit, and rectenna design are fundamental problems to guarantee a satisfying received power conversion efficiency in the MPT system. Since the efficiency of the MPT receiver is closely related to the antenna array and the rectification circuits, the current research attentions mainly focus on the following design of the power combination architecture, rectification circuit topology, and rectenna array.

1) Architectures of MPT receiver

At the receiver of the MPT, the appropriate antenna array should be carefully design so that the microwave power could be effectively converted and transferred to load. The design of the receiving array antenna can be carried out starting from a

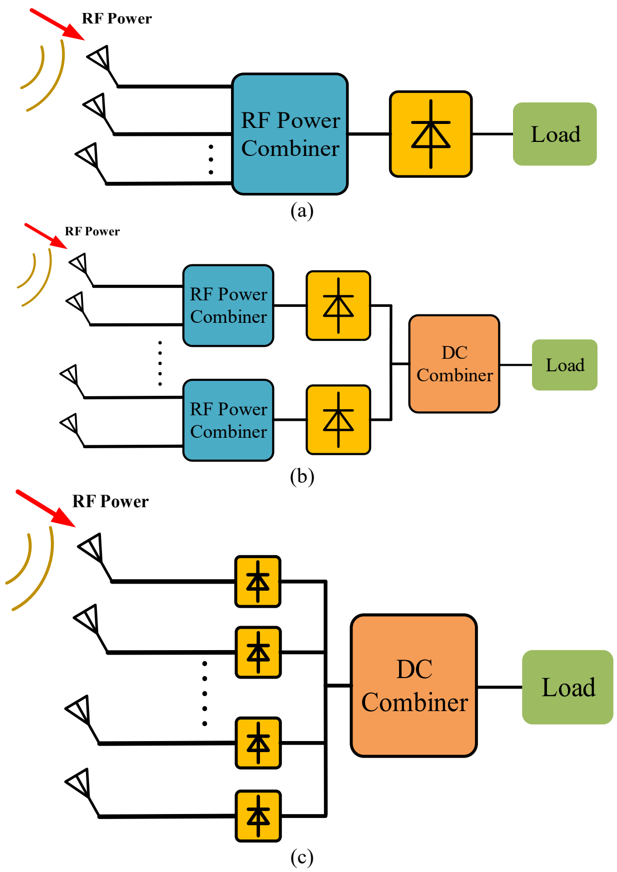

Fig.14 The architectures of MPT receiver (a) RF power combined first then rectified (b) Partial RF power combined then rectified (c) RF power rectified first then DC combined

classical phased array layout connected to an RF-DC converter at its output port [89][90]. The receiving array architectures comprise three major connection schemes, which are shown in Fig. 14. In Fig. 14 (a), this kind of architecture is characterized by high efficiency since the impinging power is coherently summed [89]. The receiving antenna comprises an RF combining network that is responsible for the in-phase combination of the incoming waves[89].

Receiver architectures that use the strategy of "combine first, then rectify" have some disadvantages, e.g., low robustness and difficulty in obtaining high-power diodes. To reduce these drawbacks, another architecture of the receiver is proposed, and the schematic of this architecture is shown in Fig. 14(b).

This architecture is also called subarray-based architecture. The overall receiving layout is divided into sub-arrangements that gather RF power and then convert the power to DC power. Subsequently, the DC power output is combined for the power summation. Some research has verified the design of this architecture. In reference [91], a set of four folded dipole antennas were combined in a dual-rhombic loop antenna subarray at the RF level. The resulting subarray has been replicated and combined in DC to synthesize an overall 4×16 receiving array; consequently, the collecting efficiency could reach 82%.

The most widely used receiving arrangement is based on a straightforward combination on the DC side; this concept is

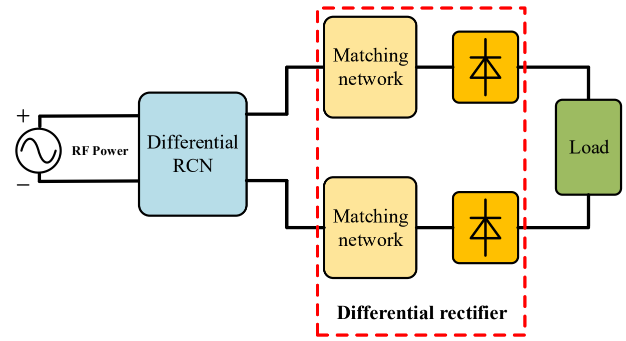

Fig. 15 Diagram of rectifier with RCN

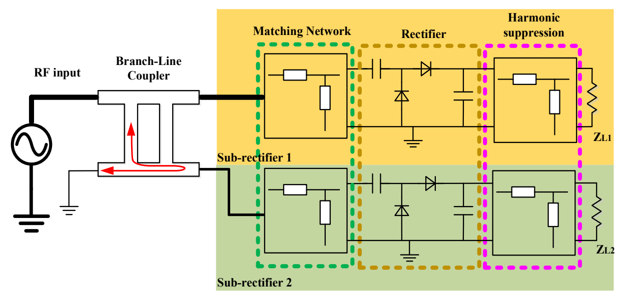

Fig. 16 Diagram of branch-line coupler strategy

shown in Fig. 14 (c). The main advantage is its simplicity; this kind of architecture yields a lower overall efficiency with respect to a coherent reception of the incident power. Several prototypes have been demonstrated in the literature that use the architecture shown in Fig. 14 (c). In reference [19], a receiving array antenna that comprises 48×48 antenna elements was developed and measured, achieving an RF-DC efficiency of approximately 50%. The DC power resulting from each antenna element, depending on different series or parallel connection schemes, is then combined. From the analysis of the literature, the variation of efficiency is 5% for the different connection schemes, such as a series or parallel layout. Another example that uses the "rectify first, then DC combine" architecture shown in the literature [92] produced a high-voltage output and nine dual-polarized patch antennas composing an independent rectification circuit. In this architecture, the DC power is combined by series schemes, and the rectification efficiency is 50% at an operation frequency of 8.51 GHz.

As analyzed above, different receiver architectures can result in different power conversion efficiency. In each kind of architecture, the RF-DC efficiency plays an essential role. Currently, rectifiers can obtain maximum efficiency only at a certain input power or constant load. Because of the nonlinearity of the diodes, a large number of higher harmonics are generated during the rectification process, resulting in impedance mismatch and rectification inefficiency. Therefore, the optimal design of a high-efficiency rectifier is essential.

2) Efficiency optimization of rectification circuits

To overcome the limitation of impedance mismatch, multiple optimization strategies have been presented. One study [93] used a resistance compression network (RCN) method to keep the rectification efficiency constant above 50% when the input power varied from approximately 5.5-33.1 dBm. The RCN was located between the input RF power source and a typical

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Table IV
Comparison of MPT rectifier

Literature	Operation Frequency (GHz)	Device	Power Level (W)	Input power range for efficiency over 50% (dB)	Peak efficiency
[26]	5.8	GaN Schotty	2.5	-	71%±4.5%
[26]	5.8	GaN Schotty	6.4	-	50%±4.5%
[61]	2.08 ~ 2.58	-	0.001 ~ 0.072 (Power range)	17.3	80.8%
[93]	0.915	HSMS2822	0.004 ~ 2 (Power range)	28	50%
[93]	0.915	HSMS2822	0.022 ~ 1.35 (Power range)	18	70%
[94]	2.45	HSMS2822 & HSMS2860	0.007 ~ 1.78 (Power range)	24	50%
[95]	2.4 ~ 2.5	GaN Schotty	2.5	-	78.2%
[96]	5.8	HSMS286	0.13	-	61%
[97]	5.8	HSMS286	0.04	10	68%
[98]	4.6	HSMS282F	0.55	6.7	60%
[99]	2.3	HSMS2820	0.25	11.8	77.2%
[100]	2.45	HSMS2860	0.03	16.2	77%

differential rectifier. The network was used to reduce the variation range of input impedance, which varied with the input power. A diagram of the rectifier with the RCN is shown in Fig. 15. Literature [93] fabricated a differential rectifier with an RCN that operated under 915 MHz. The bandwidth was 3.6 dB wider than that of the typical differential rectifier; moreover, an input power range of 13.5-31.3 dBm was obtained for efficiency ＞70%. This kind of strategy optimizes the input impedance, and then reduces the impedance sensitivity when the input power varies.

RCNs can reduce the sensitivity of rectifying efficiency to input power and load variation, and another method that uses a branch-line coupler can also achieve this goal [61]. Moreover, strategies that use a branch-line coupler can operate within wide ranges of input power, operation frequency and output load. One study [61] proposed a novel structure of a rectifier that consists of two-sub-rectifying circuits and a branch-line coupler with a grounded isolation port. When the input power, output power and operation frequency vary at the same time, it will cause impedance mismatches. The branch-line coupler strategy can reuse the reflected power and improve the efficiency. Fig. 16 shows the diagram of this strategy.

Two identical sub-rectifiers are connected to the output ports of a branch-line coupler. The proposed topology is able to improve the matching performance and reduce the power loss due to impedance mismatch. Furthermore, when the operation frequency varies, the magnitude and phase characteristics of the coupler change gradually, leading to limited efficiency improvement. To overcome this limitation, a second-order coupler was also proposed in the literature [61], which has a wider bandwidth than the first-order coupler. The power recycling strategy proposed elsewhere in the literature [94] is similar to the branch-line coupler strategy mentioned above. By using the branch-line coupler, the power reflected from the two main branches can be efficiently transmitted to the power recycling branch. Consequently, the power can be reused, and the rectification efficiency is improved. In order to further improve the efficiency of MPT receiver, the receiving antenna and rectification circuits are usually combined, called rectenna.

3) Rectenna design

The research and development of improved rectenna arrays is one of the most promising research fields in current MPT

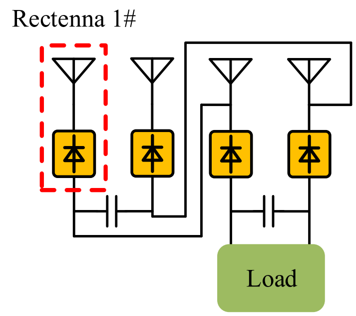

Fig. 17 Diagram of cascade scheme

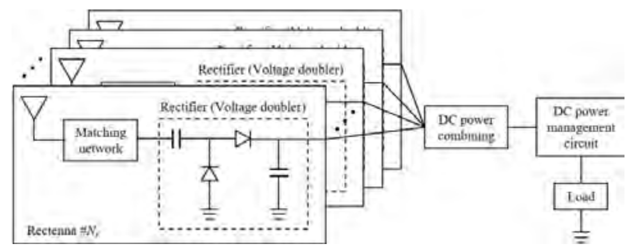

Fig. 18 Parallel DC power combing method proposed in [29]

receivers. Several prototypes have been demonstrated in the literature that comply with the architecture of the rectenna. In this framework, a rectenna array structure has been proposed for energy harvesting [88]. Considering the reduction of the size of the MPT receiver, a three-element compact rectenna architecture working at 9.3 GHz was proposed [101]. A reception efficiency of 21% was obtained by means of a planar arrangement comprising a slot antenna and rectifying circuit, and DC power was obtained by each antenna using a cascade scheme. A diagram of the cascade scheme is shown in Fig. 17. In other kinds of application scenarios, compact rectenna arrays are widely used. For instance, in reference [102], a self-biased adaptive reconfigurable rectenna is proposed. In such cases, the states of the p-i-n switch can be automatically changed in order to connect/disconnect the matching stub. Therefore, the rectification circuit could improve impedance matching performance at different power levels.

Moreover, a microwave power beam that was radiated from an enlarged transmitting antenna was formed into a Fresnel zone rather than a far-field region at a midrange of several meters. In the Fresnel region, the conventional far-field beamforming method cannot generate a suitable beam and exhibits beam gain degradation. Thus, in the near-field, the beam focused method has to be applied to improve the power transfer efficiency. When the receiver is in the Fresnel region of the transmitting array, the power focused point is constructed at the location of the receiver with the contributions of the array elements sum in phase [103][104]. In the receiver, the antennas should be arrayed to further improve the power transfer efficiency. In reference [29], a parallel DC power combining rectenna array method is used since the conventional rectenna that used RF combined array antennas has several problems under the influence of the near-field effect [105]. Rectenna arrays that use a parallel DC power combining method noncoherently sum the power received from each antenna element [29]. The structure of parallel DC power combination is presented in Fig. 18. Since the MPT transmitter allows power focusing in the near-field, the optimal method of a rectenna structure with regard to the size of the focal spot can be proposed. In this structure, a DC power management circuit is also cascaded after the rectenna. The rectifier is designed as a voltage doubling rectification circuit, and the DC power management circuit has the function of maximum power point tracking (MPPT) to maximize the rectification efficiency by load variation.

Similar approaches have also been employed for the design of rectenna structures, such as stacked differential rectennas and the stacked structure concept [106], yielding a high efficiency and low-complexity rectenna under an operation frequency of 5.8 GHz. In fact, more than 40% rectification and 0.041 W/m^2 power density are also achieved.

Another kind of series and/or parallel connection of the differential rectenna units is presented in [107], in which the series and/or parallel connected rectenna arrays are reported to provide a high voltage and large current; moreover, this kind of connection attains 38% conversion efficiency under the low RF power density of 0.03 W/m^2, and the operation frequency is also 5.8 GHz.

Concerning the analysis above, the rectenna array design and MPPT techniques suitable for the MPT system are still valuable research topics in the future. The comparison of MPT rectifier is shown in Table IV.

IV. Open Research Issues and Future Trends

A. Safety issues of MPT system

Many people are concerned about situations such as “microwave power beam becomes out of control,” or “people enter a room with high-power beam”. Therefore, a safety beam detection and cut-off system are developed [108]. The system consists of two safety mechanisms: 6 sensors for beam detection on the outside of the rectenna and LED sensors for the detection of unexpected objects entering the power beam area. When a person enters microwave power transmission area, the cut-off system could automatically cut off the beam to ensure personal safety.

Regarding safety regulations, different countries have different standards. In China, the government has introduced national standards GB12638-90 and has made a safety requirement of radiation for microwave. The safe range of human body reception is below 13.7V/m. During the experiment, the operators should stand behind the transmitting antenna array and ware microwave protective suits. If people come too close to the antenna array or when they are exposed for a long time, the microwave power transmitter may do harm to the human body. As microwave power control technology gets improved in the future, more safety MPT system could be achieved.

B. Efficiency optimization

The long-range MPT system is gradually becoming a reality with the continuous development of technology. However, the overall efficiency is around 10%, which hinders the commercial development of the MPT system. The primary field for efficiency improvement is PA devices. For instance, under 5.8GHz, the PA composed of GaN devices has only 60% conversion efficiency. Although magnetron or TWT could achieve higher power level and efficiency, they have not been widely used in commercial applications due to their volume, lack of phase and amplitude control strategy and other problems.

Beam steering technology is also an important part of the MPT system, and the accuracy of beam control determines the efficiency of the entire system. For instance, charging an unmanned aerial vehicle (UAV), “accuracy of beam control” and “target detection” are two keywords describing these efforts. If the moving target cannot be accurately tracked during the microwave power transfer process, the power transfer efficiency will be greatly reduced. Thus, the calculation algorithm of the moving target’s position and the beam tracking with high dynamic characteristics are the key research content in the beam control of the MPT system.

The other essential limitation is the low efficiency of high-power rectification at receiver. At present, the rectification at 5.8GHz, even millimeter wave bands, is used by the products of Broadcom HSMS series products, and the power capacity is around the milliwatt level. In the future, the development of GaN Schottky diodes could promote the improvement of rectification efficiency and power capacity. In addition, RF synchronous rectifiers using GaN transistors are also worth attention.

C. Simultaneous power and communication transmission of MPT system

Future MPT system could most likely consist of signal and power transmission, since wireless communication is also equivalent to a low-power level transmission. By utilizing power signal as a carrier and adding the modulation information, MPT system may become a multi-use system. The capability of simultaneous transmission of information and power could offer a novel strategy for future SPS application (no additional navigation signal is required). However, how to effectively modulate information onto the microwave power is still an open problem.

V. Conclusion

In this paper, the state-of-the-art long-range MPT system is reviewed. The recent progress on MPT which developed in US, JAXA, etc. is presented. Several kinds of architectures of transmitter, receiver and multiple directional radiation methods are described in this paper. Transmitters with capability of the adjustable amplitude and phase have gradually become the mainstream of MPT systems. Moreover, the I-Q modulation used in communication field is borrowed to assist the amplitude and phase control in transmitter. In terms of directional radiation, the research of array antenna is also essential, more specifically, suitable strategies to maximize the effectiveness of retrodirective beam steering are important to enhance the efficiency and safety of MPT system. In the receiver, different structures of rectenna could bring different rectification performance. Additionally, the issues and future trends of MPT system are also provided. Future research in MPT system requires the combination of power and signal which causes the interdisciplinary research. Moreover, in the future, as transmission distance and overall efficiency increase, the MPT will embrace a wider range of commercial applications.

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