Design of Microwave Directional Heating System Based on Phased-Array Antenna

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***Abstract*— Microwave selective/localized heating has been widely used in special areas, e.g., medical treatment and food processing, but the control of selective/localized heating in restricted space, e.g., microwave ovens, is difficult to accomplish. In this article, a Giuseppe Peano fractal phased-array antenna is designed, and the phase of each radiator is derived to achieve the arbitrary spatial division of the electromagnetic field in a cavity based on the superposition principle of waves. Then, a multiphysics model of microwave heating is established by coupling the electromagnetic field and heat transfer to simulate the directional control of microwave heating in a cavity. An experimental system is built, and the heating results are measured using an infrared thermal imager to verify the temperature distribution in different spatial regions. Finally, the feasibility of the model for different heating targets is discussed.**

***Index Terms*— Direction control, directional heating, microwave heating, multiphysics simulations, phased-array antenna.**

I. Introduction

COMPARED with traditional heating methods, microwave heating has many advantages, including fast heating, selective/localized heating, easy control, small heating loss, and time savings [1]–[6]. Therefore, microwaves have been widely researched in the laboratory and have great potential in industrial applications. Although selective/localized heating may cause the problem of uneven heating, which will give rise to hot spots in the heating process, this characteristic can be used in special applications, such as medical treatment, the chemical industry, and food processing [7]–[10].

The application of selective/localized heating has been investigated by many scholars recently. Jerby *et al.* [11] applied localized microwave heating (LMH) to drilling technology and established a kind of mechanically assisted microwave drill (MWD). They applied such a type of heating to basalt to study volcanic eruption [12]. Then, he made a detailed theoretical study of LMH [13], which established the basic LMH 1D enhancement model in a cavity. LMH has also been applied in additive manufacturing (AM) and 3-D printing, and researchers have established LMH-AM technology or a localized heating character called multiwalled carbon nanotubes (MWCNTs) to realize AM of high strength [14]–[17]. Schütz *et al.* [18] used LMH as an assistive method to manufacture advanced inorganic materials. By using localized heating, Gomez *et al.* [19] successfully implanted MWCNTs into a coating to accelerate the gathering of ceramic particles. Meanwhile, selective microwave heating has been used in chemical engineering and ceramic processing to increase reaction rate [20]–[24].

Antennas are usually applied to realize the localized heating in free space. Ge *et al.* [25] proposed a multislot coaxial antenna with a π impedance-matching network to realize local heating of biological tissue, which can be used in the ablation of liver tumors. Meanwhile, microwave ablation of MWA antennas has also been investigated to realize local heating of biological tissue and treat tumors [26], [27]. Meanwhile, in order to focus microwave energy at controllable sites, phased-array antennas excited by solid-state microwave generators [28]–[32] are commonly used in free space [33], [34]. Anderson and Melek [35] simulated an orthogonal-array system to produce a focal region for spatially selective heating by changing the amplitude and phase of each radiator. Zhang *et al.* [36] computed the power deposition of a square array of four antennas with different driving phases by neglecting the coupling between each antenna. In restricted space, Cuomo *et al.* [37] proposed a phased-array antenna to generate plasma at controllable sites in the reaction chamber by controlling the phase of the individual elements. Horikoshi [38] proposed an intelligent microwave cooking oven to selectively heat lunchboxes by controlling the phase of the microwave. However, the theoretical foundation in restricted space was unreported. On the other hand, leaky-wave antennas are also used to focus the near-field beam in free space. Martinez-Ros *et al.* [39] proposed an array of symmetrically in-phase microstrip lenses to obtain near-field focused beam, and the focused site can be changed by different driving amplitudes and frequencies [40].

Manuscript received February 12, 2020; revised May 6, 2020; accepted May 29, 2020. Date of publication June 24, 2020; date of current version November 4, 2020. This work was supported in part by the National Natural Science Foundation of China under Grant 61971295 and Grant 61731013. *(Corresponding author: Huacheng Zhu.)*

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Digital Object Identifier 10.1109/TMTT.2020.3002831

In this article, the directional control of microwave heating in a cavity is introduced based on the phased-array antenna. Microwave energy is fed into the cavity through the phased-array patch antenna, and the directional heating of different regions in the cavity is realized by adjusting the phase of each radiator according to the superposition principle of waves. In Section II, the basic theory of the superposition principle of waves is introduced in order to focus the beam at controllable sites. A phased-array antenna is designed to balance high gain and low sidelobe levels. Then, a multiphysics model is established to simulate the heating process. In Section III, the driving phase of each radiator is calculated, and the electric distributions in free space and in the cavity are compared. Then, the microwave heating experiment is carried out, and the simulation and experiment results are compared. Meanwhile, the heating performances for different targets are discussed.

II. Methodology

A. Basic Theory

It is well known that when two or more electromagnetic waves of the same type are propagating at the same point, the total amplitude at the point will be the vector sum of the amplitudes of the electromagnetic waves, which is called the superposition principle of waves. If the phase of the radiator of each electromagnetic wave with the same frequency is controlled, the phase difference of each wave propagating at the same point can be an even multiple of π. Then, the total amplitude is the sum of the individual amplitudes, and the beam can be focused at the point. Therefore, with the controllable phase of each radiator, phased-array antennas can be used to realize directional heating at controllable points in free space. On the other hand, in restricted space, e.g., a microwave oven, different patterns will be formed due to the reflection of the electromagnetic waves, and it will be difficult to focus the beam at controllable points. However, if there exists a load at this point, the reflection of the waves will be small, and the superposition principle of waves may be valid to realize the directional heating in a metal cavity.

As shown in Fig. 1, the radiators are arranged on the xOy plane in the form of a rectangular array. The center point of the array is set at the origin site of the coordinate system. The distances between the x- and y-directions of the array elements are d_x and d_y, respectively. Let the distances between the array element $M_{(k,l)}$ and the original site O in the x- and y-axis directions be kd_x and ld_y, respectively. Let the spherical coordinates of the near-field superposition point $R_{(r,\theta,\varphi)}$ be (r, θ, φ), and the corresponding rectangular coordinates are marked as (R_x, R_y, R_z). For the convenience of calculation, the distance from the origin site to the near-field superposition point is taken as the reference distance with the length of r. It can be seen that the distance from each radiator to $R_{(r,\theta,\varphi)}$ is different. The distance difference between element $M_{(k,l)}$ and the original site to $R_{(r,\theta,\varphi)}$ is given by

$$\begin{aligned}\Delta d_{(k,l)} &= |\overrightarrow{MR}| - |\overrightarrow{OR}| \\ &= \sqrt{(R_x - kd_x)^2 + (R_y - ld_y)^2 + R_z^2} - \sqrt{R_x^2 + R_y^2 + R_z^2}.\end{aligned} \tag{1}$$

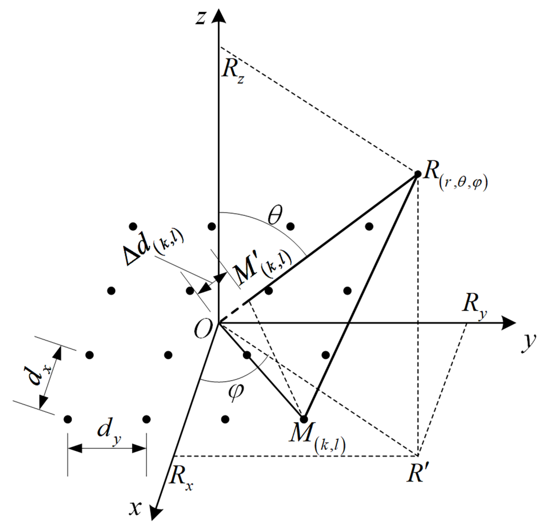

Fig. 1. Schematic of the superposition principle of waves.

If the phase difference of each wave propagating at the same point is the same, the phase difference $\Delta\psi_{(k,l)}$ between the radiator and the origin site can be given by

$$\begin{aligned}&\Delta\psi_{(k,l)} \\ &= k_0 \Delta d_{(k,l)} \\ &= \frac{2\pi f}{c}\sqrt{(R_x - kd_x)^2 + \left(R_y - ld_y\right)^2 + R_z^2} \\ &\quad - \frac{2\pi f}{c}\sqrt{R_x^2 + R_y^2 + R_z^2} \\ &= \frac{2\pi f}{c}\sqrt{(r\sin\theta\cos\varphi - kd_x)^2 + \left(r\sin\theta\sin\varphi - ld_y\right)^2 + (r\cos\theta)^2} \\ &\quad - \frac{2\pi f r}{c}\end{aligned} \tag{2}$$

where k_0 is the wavenumber, f is the frequency, and c is the velocity of light. According to (2), once the focused point and the distance among each radiator are determined, the phase of each radiator can be obtained. In a metal cavity, we may also apply this equation to achieve the arbitrary directional heating if there exists a load at the controlled point.

B. Phased-Array Antenna

The radiator unit should be compactly designed to concentrate the electromagnetic energy in the targeted heating region. As shown in Fig. 2, the proposed radiator utilizes the Giuseppe Peano fractal-shaped patches [41] that are printed on FR-4 substrates of 5-mm thickness. The radiator is fed with a 50-Ω N-type connector. In the Giuseppe Peano fractal, two zigzag sections with a total length of f_1 are formed in the central part of a segment with a length of f_2. The length ratio $n = f_2/f_1$ is defined as a fractal proportion. By adjusting the radiator's structure parameters, such as the size of the patch, fractal proportion, and position of the feeding point, the radiator resonates at 2.45 GHz and has a good radiation pattern.

In order to reduce the mutual coupling between the radiator elements, the distance of the array unit is usually more than

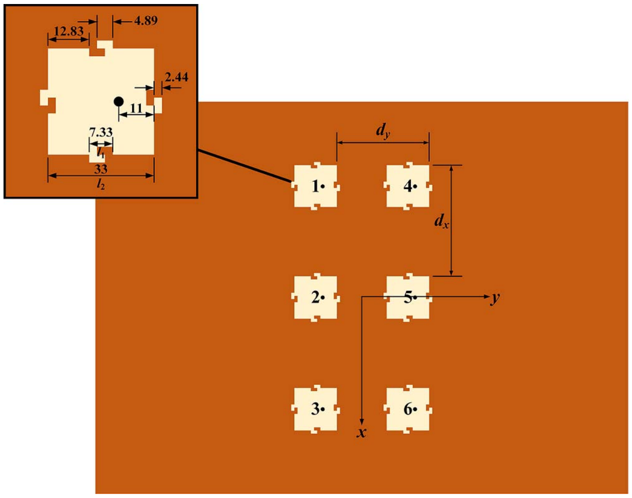

Fig. 2. Structure and dimensions of phased radiator array (unit: mm).

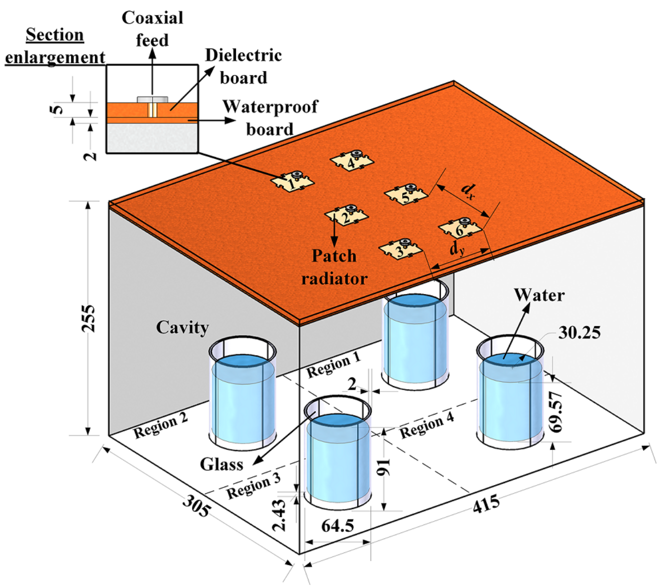

Fig. 3. Geometry of 3-D simulation model (unit: mm).

half a wavelength. Based on the proposed radiator and pattern-synthesis principle, a 3×2 radiator array is designed and fabricated, as shown in Fig. 2. To balance high gain and low sidelobe level, the distance between two adjacent radiator elements along the x-direction is $d_x = 86.75$ mm and that along the y-direction is $d_y = 71.75$ mm.

C. Multiphysics Modeling

In Section II-B, the distance between each radiator is determined. Once the focused point of the beam is calculated, the driving phase of each radiator will be given by (2). In this work, the dimension of the cavity is based on a type of microwave oven (X7–321D, Guangdong Midea Kitchen Appliances Manufacturing Company Ltd., Foshan, China). COMSOL 5.4 is used to perform the multiphysics coupling simulation of electromagnetic and heat transfer in the heating process. The geometry of the simulation model is shown in Fig. 3, including a metal cavity with a bottom divided into four virtual areas that are designated regions 1–4, a dielectric plate as a dielectric board for the antenna, a phased-array antenna consisting of six metal-patch antenna elements, a waterproof board, and four glass cups of 200-ml water. Microwaves are fed through six coaxial feeders connected to the radiators. The four cups of water are located in the center of the bottom of each virtual area. Therefore, the focused points in this cavity are assumed to be the center points of the four areas on the bottom.

In the simulation, the electromagnetic field and heat transfer are coupled. To calculate the electromagnetic field, Maxwell's equations are used [42]

$$\begin{aligned} \nabla \times \vec{H} &= \vec{J} + \frac{\partial \vec{D}}{\partial t} \\ \nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ \nabla \cdot \vec{B} &= 0 \\ \nabla \cdot \vec{D} &= \rho_e \end{aligned} \tag{3}$$

where $\vec{H}$ is the magnetic field intensity, $\vec{J}$ is the Ampere density, $\vec{E}$ is the electric field strength, t is the time, $\vec{B}$ is the magnetic induction intensity, $\vec{D}$ is the electric displacement vector, and ρ_e is the electric charge density. Then, the electromagnetic power loss Q_e can be gained from the computed electric field by the following equation [43], [44]:

$$Q_e = \frac{1}{2}\omega\varepsilon_0\varepsilon''\left|\vec{E}\right|^2 \tag{4}$$

where ε'' is the imaginary part of the permittivity of the processing material.

The electromagnetic power loss is converted into heat, and the temperature distribution can be calculated by [45]–[47]

$$\rho_m C_p \frac{\partial T}{\partial t} - k_m \nabla^2 T = Q = Q_e \tag{5}$$

where ρ_m is the density, C_p is the heat capacity, T is the temperature, Q is the heat source, and k_m is the thermal conductivity.

In the simulation, only the water and the glass cups are heated by microwaves. The upper surface of the water and the walls of glass cups exchange heat with air, which is given by the boundary condition

$$-k_m \frac{\partial T}{\partial n} = h(T - T_{\mathrm{air}}) \tag{6}$$

where $\partial T/\partial n$ is the gradient of the temperature perpendicular to the interface, h is the heat transfer coefficient with the value of 10 W/m$^2 \cdot$ K, and T_{air} is the temperature of the air with the value of 293.15 K.

In this model, the frequency of the electromagnetic wave is 2.45 GHz, and the electromagnetic-wave power output of each radiator is 50 W. The entire cavity is filled with air. The initial temperature of the water is 293.15 K. Related input parameters of the simulation are shown in Table I.

III. Results and Discussion

A. Spatial Division of Electromagnetic Field

1) Reflection of Each Radiator: The designed radiator, as shown in Fig. 2, is simulated and tested. The experiment

TABLE I
SUMMARY OF MATERIAL PROPERTIES APPLIED IN THE MODEL

Domain	Property	Value	Source
Water	Relative permittivity	80-12j	
	Relative permeability	1	
	Conductivity (S/m)	5.5×10^{-6}	
	Heat capacity at constant pressure (J/kg·K)	4.18×10^{3}	
	Density (kg/m^3)	1×10^{3}	
	Heat conductivity coefficient (W/m·K)	0.62	
Polytetrafluoroethylene (PTFE)	Relative permittivity	2.08	
	Relative permeability	1	
	Conductivity (S/m)	0	
Dielectric substrate/ waterproof	Relative permittivity	2.55	
	Relative permeability	1	[48]-[49]
	Conductivity (S/m)	0	
Glass	Relative permittivity	4.2	
	Relative permeability	1	
	Conductivity (S/m)	0	
	Heat capacity at constant pressure (J/kg·K)	730	
	Density (kg/m^3)	2.21×10^{3}	
	Heat conductivity coefficient (W/m·K)	1.4	
Air	Relative permittivity	1	
	Relative permeability	1	
	Conductivity (S/m)	0	

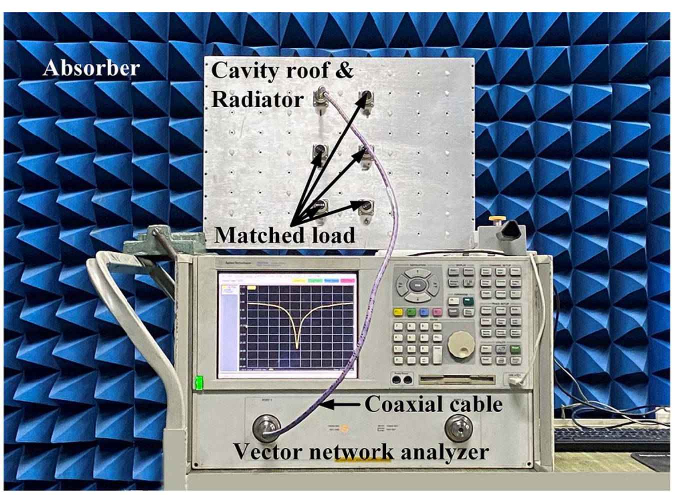

Fig. 4. Reflection coefficients measurement system in free space.

of free space is carried out in an anechoic chamber, and the reflection coefficient is tested by a vector network analyzer (N5230A, Agilent Technologies, USA), as shown in Fig. 4. The simulated and measured reflection coefficient of each radiator element in free space is shown in Fig. 5. The simulated

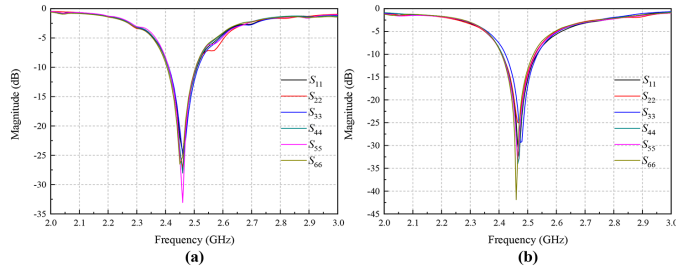

Fig. 5. Simulated and measured reflection coefficient of the radiator element in free space. (a) Simulated results. (b) Measured results.

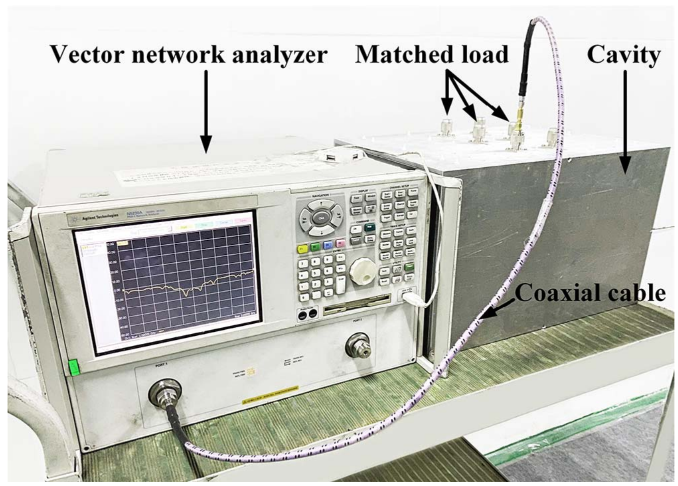

Fig. 6. Reflection coefficients measurement system in the loaded cavity.

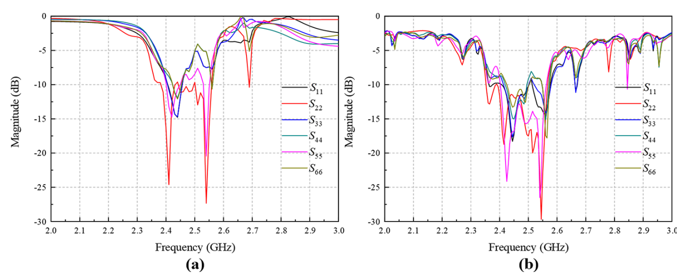

Fig. 7. Simulated and measured reflection coefficient of the radiator element in the loaded cavity. (a) Simulated results. (b) Measured results.

frequency of $|S_{11}| < -10$ dB ranges from 2.4 to 2.5 GHz with a reflection coefficient of $-25\sim-30$ dB at 2.45 GHz. All six radiator elements have a low measured reflection coefficient at 2.45 GHz, and the inconsistency of the measured reflection coefficients for the six ports is due to the error of manufacture.

The reflection coefficient in the loaded cavity, as shown in Fig. 3, is also simulated and tested. The experimental setup is shown in Fig. 6, and the simulated and measured reflection coefficients of each radiator element in the loaded cavity are shown in Fig. 7. It can be seen that the oscillation frequency of each radiator is shifted due to the reflection of electromagnetic waves, and the magnitude of the reflection coefficient is about -10 dB at 2.45 GHz in the simulation. In the application of high-power microwaves, energy efficiency is acceptable. In the experiment, the magnitude of the reflection coefficient is much

TABLE II
PHASE OF EACH RADIATOR WITH DIFFERENT SPATIAL DIVISIONS (UNIT: rad)

Region \ Radiator	1	2	3	4	5	6
1	0.270	0.765	2.446	-1.108	-0.564	1.258
2	-1.108	-0.564	1.258	0.270	0.765	2.446
3	1.258	-0.564	-1.108	2.446	0.765	0.270
4	2.446	0.765	0.270	1.258	-0.564	-1.108

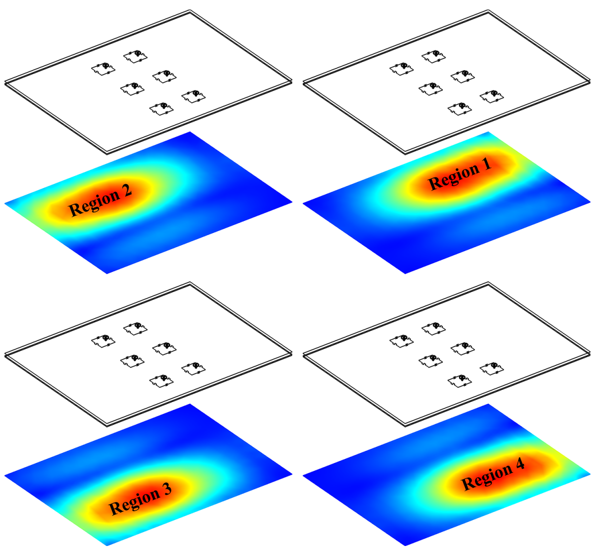

Fig. 8. Electric field distribution across the reference plane in free space.

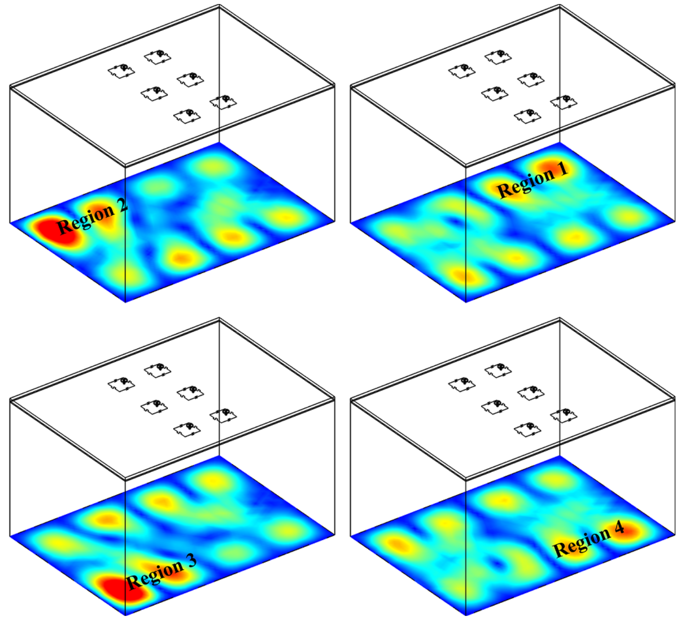

Fig. 9. Electric field distribution across the reference plane in the unloaded cavity.

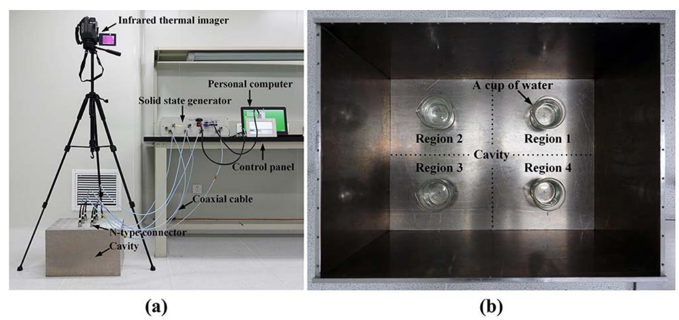

Fig. 10. Experimental setup. (a) Whole system. (b) Cavity.

better, and less than 10% of the energy fed by each radiator is reflected at 2.45 GHz.

2) Phase of Each Radiator: In order to focus the beam on each center of the four areas on the bottom of the cavity, the phase of each radiator is calculated according to the dimension of the cavity and (2), as shown in Table II. A reference plane is defined with a position 255 mm below the radiator, which is the total height of the cavity. The electric field distribution across the reference plane in free space is shown in Fig. 8. It can be seen that, by setting the radiator elements with the proper feeding phase, the radiation beam can be focused on four different regions across the reference plane in free space. On the other hand, the electric field distribution of the bottom in the unloaded cavity is shown in Fig. 9. It can be seen that the mixing patterns of the electromagnetic waves can focus a beam in the cavity, which can be used to realize the directional heating, even though there exists a weak electric field in the other regions due to the reflection of electromagnetic waves.

B. Microwave Heating

1) Experimental Setup: The experimental system mainly consists of two parts—the microwave source and the heating cavity—that are connected by six coaxial lines. A photograph of the experimental system is shown in Fig. 10. According to the simulation model, the microwave generator in the experiment consists of at least six phase-controlled, frequency-stable, and power-controllable channels. The solid-state generator has the advantages of high microwave-spectrum quality, small size, low operating voltage, easy control, and long life. Therefore, a solid-state generator (Chengdu Wattsine Electronic Technology Company Ltd., Chengdu, China) is used in the experiment. The maximum error of the output frequency of the microwave generator is ± 50 ppm, the maximum error of the output power is 3%, and the adjustable step of phase is 5.6° (about 0.0977 rad). The internal structure of the solid-state generator and phase-control interface of the microwave source are shown in Fig. 11. The signal is divided by a power divider and then fed into six-phase shifters, respectively. By controlling the phase shifters, the output of each phase shifter is fed into an amplifier. Each output signal of the amplifier is transmitted to each radiator through the coaxial line with the same length. It is worth noting that a circulator with a load is applied in the microwave generator to protect each amplifier.

2) Experiment Verification: In the experiment, four cups of 200-ml distilled water in the cavity are heated by controlling the phase of each radiator, as shown in Table II. The heating time is set as 3 min, and the output power of each radiator is 50 W. By comparing the surface temperatures of each

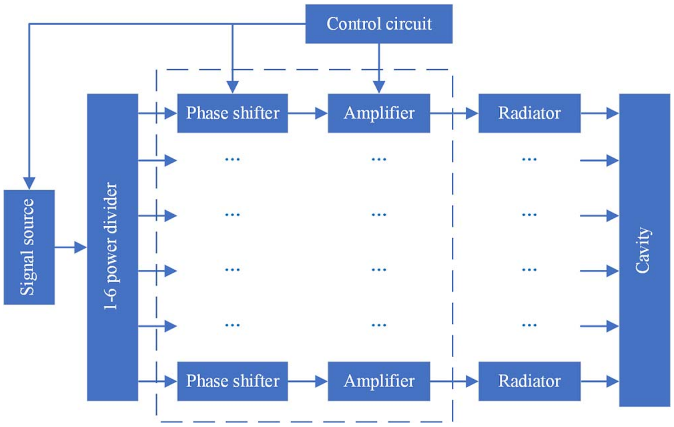

Fig. 11. System flowchart.

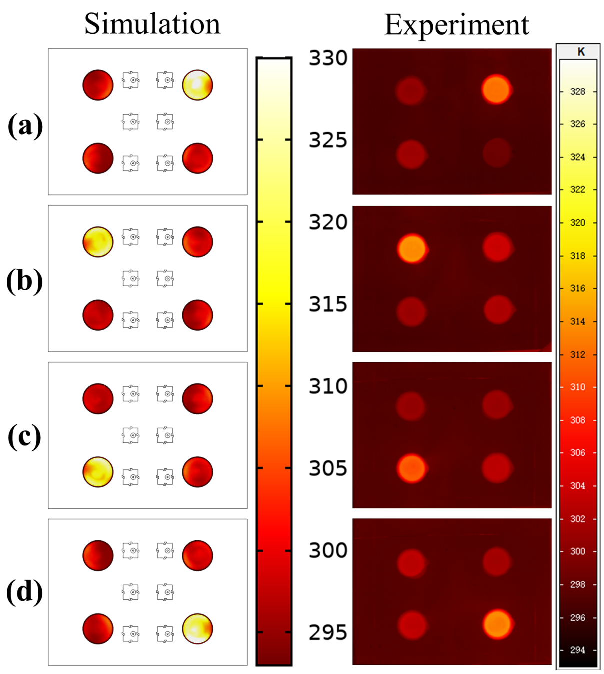

Fig. 12. Comparison of surface-temperature distributions of the simulation and experiment among four cups of 200-ml water target regions (a) 1, (b) 2, (c) 3, and (d) 4 (unit: K).

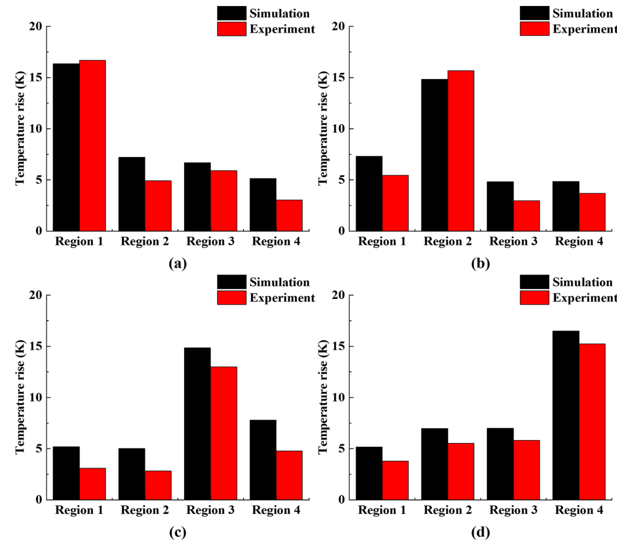

Fig. 13. Comparison between the simulation and experimental temperature rises among four cups of 200-ml water in target regions (a) 1, (b) 2, (c) 3, and (d) 4.

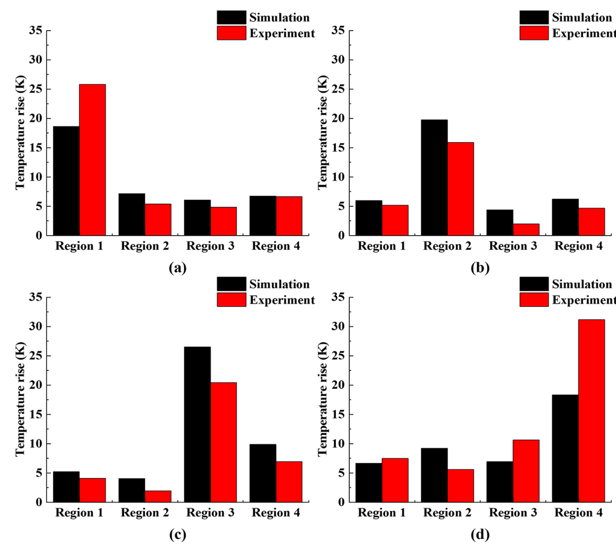

Fig. 14. Comparison between the simulation and experimental temperature rises among three cups of 200-ml water and one cup of 100 ml water in target regions (a) 1, (b) 2, (c) 3, and (d) 4.

cup of water in the simulation and experiment, as shown in Fig. 12, it can be verified that the phased-array antenna can be used to achieve selectively directional heating in the cavity. By comparing the average temperature rise of each cup of water in the experiment and simulation, as shown in Fig. 13, it is indicated that the selectively directional heating effect is remarkable. The simulation and experimental results show that the heating can be successfully performed according to the predetermined heating regions 1–4.

3) Different Load Heating: In order to verify the robustness of the heating performance of the calculated phase of each radiator, the measurement of a different load heating process is carried out. All the other parameters are kept the same with the ones in the verification experiment. In the first experiment, the cup of 200-ml water in region 3 is changed by a cup of 100-ml water. The simulation and experiment results of the mean temperature rise of each cup of water are shown in Fig. 14. In the second experiment, all the loads are replaced by 100-ml water, and the simulation and experiment results of the mean temperature rise of each cup of water are shown in Fig. 15. The results show that selectively directional heating can be realized according to the predetermined heating regions 1–4. Furthermore, it can be seen that, in the different cases, with the fixed phase of the radiator, a selectively directional energy beam can be formed in the cavity to achieve directional heating of the load (heated target) in a specified direction. With the fixed phase, the load can be replaced, and the stability can still be maintained. On the other hand, due to the difference in microwave energy absorption caused by the volume change of the heated object,

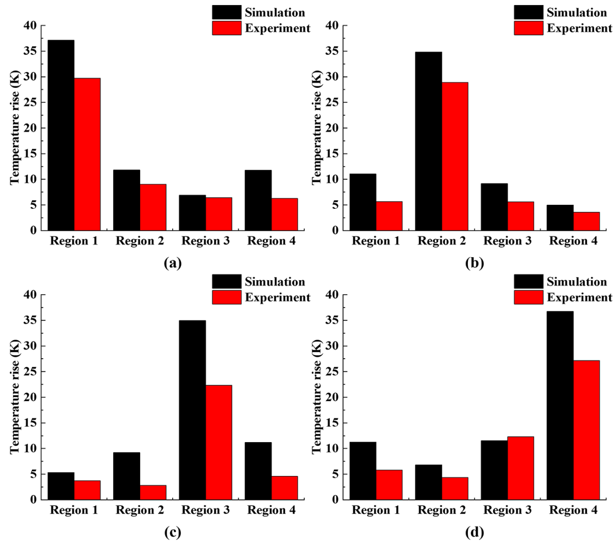

Fig. 15. Comparison between the simulation and experimental temperature rises among four cups of 100-ml water in target regions (a) 1, (b) 2, (c) 3, and (d) 4.

the heating intensity changes, and the case with a smaller volume of the water column can achieve a higher average temperature rise.

IV. Conclusion

In conclusion, a phased-array-based cavity that can realize selectively directional heating in a cavity is designed. By controlling the phase of the electromagnetic wave fed into the cavity based on the superposition principle of waves, the pattern synthesis of the electric field is carried out to form a pointing beam in the cavity, so as to realize the selectively directional heating of different regions and different loads. According to the theoretical calculations, multiphysics simulation, and comparison with multigroup experiments, the design of a selectively directional heating system is successfully verified. This work is based on the application of the microwave oven, and the total power is about 1 KW. Therefore, the power capacity of each radiator is about 200 W. On the other hand, this procedure can be extended to other types of antennas for higher power if the power capacity of antennas is high enough. However, the heating system also has some shortcomings, such as the high manufacturing cost of the solid-state generator and the high precision required by the phase control of each port of the radiation unit, which all must be improved in the next stage of work.

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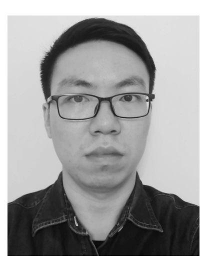

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