Dual feeding cavity resonator for efficiency enhancement in liquid heating applications

A.A. Abduljabar[✉], H. Choi and A. Porch

A new type of microwave resonator feeding topology is proposed to enhance the power delivered to a lossy sample for microwave heating applications. The method uses two input signals with equal phase and magnitude, instead of the usual one input. As a result, for the same total input power, the delivered power can be increased to twice the power than the case of the one input. A 2.45 GHz TM_{010} cylindrical cavity with dual input ports is used to heat a water sample with a total input power of 0.25 W. The efficacy of the proposed heating topology was verified by 3D electromagnetic simulation and heating measurements, including *S*-parameters, incident and reflected power, and thermal images. All measurement results support the increase in heating efficiency in the two port case, while using the same total amount of power as for the one port case.

Introduction: The heating of polar liquids by using microwave electromagnetic energy has been popular in many industrial and scientific applications. The two main significant advantages of microwave heating are its selectivity, where the electromagnetic energy can be delivered to the sample without heating other parts of the system, and its non-contacting nature, where the sample can be heated and cooled faster than the other traditional heating methods.

Several microwave heating techniques have been presented for various applications. In [1], an integrated microstrip transmission line was used to generate spatial temperature gradients in a polymeric microfluidic device. A re-entrant cylindrical microwave cavity was adopted to design a microwave microfluidic heating system to perform polymerase chain reactions [2]. A microwave resonator was presented in [3] as a sensor and heater of individual nano-litre-sized droplets generated in microfluidic channels. A new microwave wireless heating technique was proposed in [4] which can be used in healthcare applications. A microwave nano-litre scale liquid heater was presented in [5] which works at 20 GHz in a digital microfluidic system. A new approach was proposed in [6] in which the coupling of the microstrip double-split ring resonator can be electronically controlled to improve the heating efficiency of the liquid in microfluidic system.

In this Letter, we propose a new topology for microwave heating applications in which the heating efficiency can be improved. The approach consists of two input excitations with equal magnitude and phase, instead of the usual one as shown in Fig. 1. This approach has been applied to a TM_{010} cylindrical cavity at 2.45 GHz, which has two input feeds which are symmetric and opposite to each other.

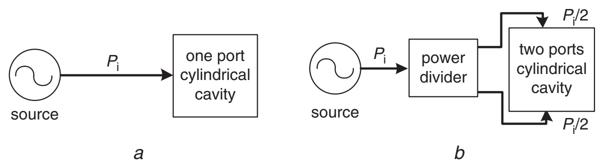

Fig. 1 *Block diagram of two types of cavity excitation. P_i indicates total power available from signal source*

a One input
b Two inputs

Cavity design and performance: An aluminium cylindrical cavity resonator was designed and fabricated with an internal radius of 46 mm and height of 40 mm, as shown in Fig. 2. The two inputs are inductive loops with diameters of 7 mm, made from wire of 0.8 mm diameter. This cavity resonator is used to heat the water sample in a quartz capillary, which has an inner diameter of 1 mm and outer diameter of 1.2 mm. The measured *S*-parameters of the cavity resonator with one and two inputs are shown in Fig. 3. A hole of diameter 15 mm was drilled in the side wall of the cavity for the thermal imaging camera, as shown in Fig. 2. A quartz capillary with the relative permittivity (ε_r) of 3.8 was inserted vertically through two holes on the top and the bottom of the cavity centre to obtain the maximum liquid polarisation by placing the sample along the axis, where the electric field intensity is at the maximum. The diameter of the inductive coupling loop was set to obtain approximately critical coupling with the empty capillary where the resonant frequency and the quality factor are 2.497 GHz and 1000, respectively, where the unloaded Q is very high, reduced to 1000 by strong coupling. The presence of the water sample in the cavity resonator reduces the resonant frequency and the quality factor to 2.462 GHz and 213, respectively, and the S_{11} at resonance changes to −2.5 dB. This low value of the coupling limits the heating efficiency, which can be improved as illustrated in the next section.

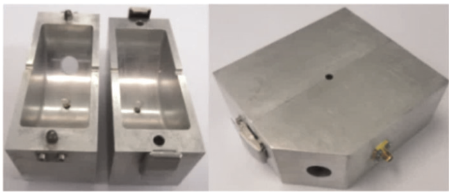

Fig. 2 *Photograph of cylindrical waveguide cavity with two input and hole for thermal camera monitoring*

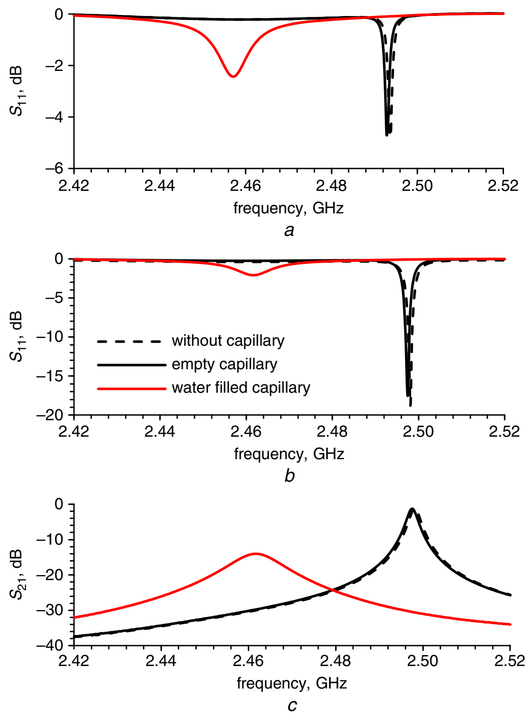

Fig. 3 *Measured S-parameters of cylindrical cavity resonator at 25°C*

a $|S_{11}|$ of one-port feeding
b $|S_{11}|$ of two-port feeding
c $|S_{21}|$ of two-port feeding

Experimental set up, results, and discussion: To prove the efficacy when using dual input excitations, which is proposed to improve heating efficacy, three sets of the results are presented in this section. Results include the 3D simulation of the electric field distribution in the cavity resonator, incident and reflected power, and the thermal imaging camera measurements.

Starting with the simulation results of the electric field distribution of the vertical cross section of the cavity resonator by using COMSOL multiphysics software, the simulation was conducted for two cases: one-port input power of 24 dBm and two-port input power of 21 dBm for each port. As shown in Fig. 4 with colour scale from 0 V/m (blue colour) to 4 kV/m (red colour), the electric field intensity has been enhanced in the case of the two-port feeding inputs from 2.5 to 3.5 kV/m at the centre of the cavity resonator. This means an increase in the delivered power to the cavity resonator and, consequently, an increase in the heating rate of the sample.

The second set of results comprises measurements of the incident and reflected power of the cavity resonator. The block diagram of the microwave heating system is shown in Fig. 5. The system was set to deliver 24 dBm to the cavity resonator through one-port or two-port inputs, while the incident power, the reflected power, and the sample temperature were monitored. The system consists of the RF signal generator (Keysight Technologies N5181B MXG), the power amplifier

(MILMEGA AS1860-100) with the gain of 46 dB over 1.8–6.0 GHz, and the circulator used to protect the power amplifier from the reflected power. A 30 dB directional coupler with two power sensors (Keysight Technologies NRP-Z22) was utilised to monitor the incident and the reflected powers from the cavity resonator, as shown in Fig. 5.

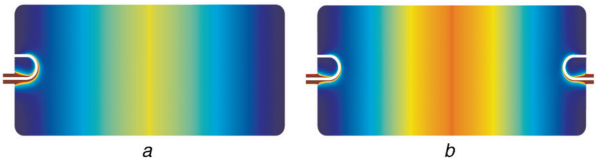

Fig. 4 *Electric field distribution in cavity resonator with water sample at 25°C in case of*

a One-port excitation (24 dBm) at 2.457 GHz
b Two-port excitation (21 dBm for each port) at 2.462 GHz

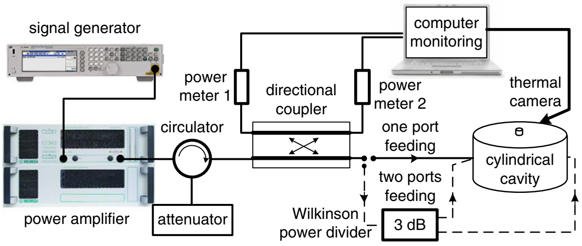

Fig. 5 *Block diagram of experimental setup of one-port (solid line) and two-port (dashed line) feeding*

An in-phase, two-way power divider (Wilkinson power divider) was used to divide the input signal in the case of two input ports. The signal generator was set to generate a frequency sweep from 2.443 to 2.483 GHz, with the frequency step of 0.2 MHz and a dwell time of 2 s. The measurements were conducted for two cases: one-port and two-port inputs. The reflected power as a function of frequency measured by using a power sensor for both cases is presented in Fig. 6*a*.

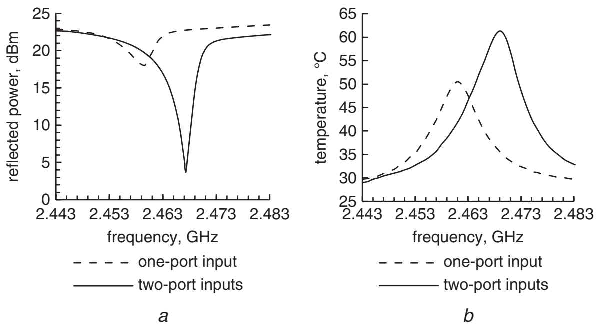

Fig. 6 *Heating efficiency comparison for*

a Reflected power
b Sample temperature

Also, the thermal imaging camera (Micro-Epsilon TIM640) was set up through the hole on the side wall of the cavity resonator to monitor the temperature difference between the two cases. The change in the sample temperature over the frequency sweep for both cases is presented in Fig. 6*b*, and the thermal images of the maximum temperature are shown in Fig. 7. It can be seen in Figs. 6*a* and *b* that the minimum reflected power in case of one-port input is 18 dBm at resonant frequency of 2.46 GHz, when the maximum temperature is 50.5°C. The corresponding value of the S_{11} calculated from the incident and the reflected power measurements is −6 dB. The reason why this value is different from the result in Fig. 3*a*, which is −2.5 dB, is due to the increase in the sample temperature which leads to a decrease in the loss (as expected by the Debye model for water).

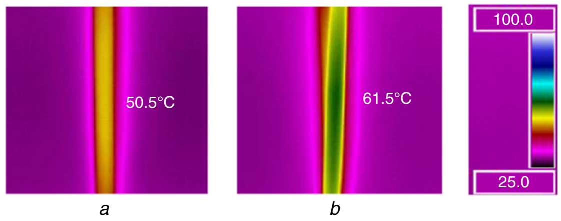

Fig. 7 *Thermal images of maximum sample temperature for same input power of 24 dBm*

a One-port input
b Two-port inputs

In case of two-port inputs, as shown in Figs. 6*a* and *b*, a large increase in the heating efficiency is achieved where the minimum reflected power is 3.77 dBm at 2.467 GHz, and the resulting maximum temperature is 61.5°C. The equivalent S_{11} for this value of the reflected power is −21.14 dB. The shift in the resonant frequency between the two cases comes from two factors. Firstly, the presence of the second coupling loop, which slightly increases the resonant frequency. Secondly, the major change comes from the temperature dependence of the complex permittivity of the water, in which the real part of its complex permittivity decreases with increasing temperature. The performances of the two input topologies are summarised in Table 1.

Table 1: Summary of heating performance of two-ports heating topologies

Feeding type	f_r (GHz)	Reflected power (dBm)	Temperature (°C)	S_{11}, dB
One port	2.460	18.00	50.5	−6.00
Two ports	2.467	3.77	61.5	−21.14

Conclusion: It is proved that for the same input power a simple variation in the topology, namely two-port inputs with the help of an in-phase two-way power divider, can increase the heating efficiency in a microwave heating system. The proposed topology was applied to a cylindrical cavity resonator used to heat a water sample in a quartz capillary. The experimental results including the incident/reflected power and thermal imaging together with 3D electromagnetic simulation support the efficacy of the proposed two-port inputs in maximising the power delivered to the sample.

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One or more of the Figures in this Letter are available in colour online.

A.A. Abduljabar (*College of Engineering, University of Basra, Basra, Iraq*)

✉ E-mail: aliaiq76@gmail.com

H. Choi and A. Porch (*School of Engineering, Cardiff University, Cardiff CF24 3AA, Wales, United Kingdom*)

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