Introducing an electromagnetic cooking device that includes an enclosed cavity for heating and preparing food. The device consists of a set of radio frequency feeds configured to introduce electromagnetic radiation into the cavity. These feeds, along with high-power amplifiers coupled to the set of radio frequency feeds, amplify the signal to levels sufficient for cooking activities. A controller manages the operation, ensuring safe and efficient cooking processes. The device is designed to be versatile, catering to diverse cooking needs and preferences.
METHOD AND DEVICE FOR ELECTROMAGNETIC COOKING

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority to U.S. Provisional Patent Application No. 62/170,416, filed on June 3, 2015, the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] The present device generally relates to a method and device for electromagnetic cooking, and more specifically, to a method and device for determining and controlling the resonant modes within a microwave oven.

[0003] A conventional microwave oven cooks food by a process of dielectric heating in which a high-frequency alternating electromagnetic field is distributed throughout an enclosed cavity. A sub-band of the radio frequency spectrum, microwave frequencies at or around 2.45 GHz cause dielectric heating primarily by absorption of energy in water.

[0004] To generate microwave frequency radiation in a conventional microwave, a voltage applied to a high-voltage transformer results in a high-voltage power that is applied to a magnetron that generates microwave frequency radiation. The microwaves are then transmitted to an enclosed cavity containing the food through a waveguide. Cooking food in an enclosed cavity with a single, non-coherent source like a magnetron can result in non-uniform heating of the food. To more evenly heat food, microwave ovens include, among other things, mechanical solutions such as a microwave stirrer and a turntable for rotating the food. A common magnetron-based microwave source is not narrowband and not tunable (i.e. emits microwaves at a frequency that is changing over time and not selectable). As an alternative to such a common magnetron-based microwave source, solid-state sources can be included in microwave ovens which are tunable and coherent.

SUMMARY

[0005] In one aspect, an electromagnetic cooking device includes an enclosed cavity; a set of radio frequency feeds configured to introduce electromagnetic radiation into the enclosed cavity to heat up and prepare food; a set of high-power radio frequency
amplifiers coupled to the set of radio frequency feeds, each high-power amplifier comprising at least one amplifying stage configured to output a signal that is amplified in power with respect to an input radio frequency signal, a signal generator coupled to the set of high-power radio frequency amplifiers for generating the input radio frequency signal, and a controller. The controller is configured to cause the signal generator and selected ones of the set of high-power amplifiers to output a radio frequency signal of a selected frequency, a selected phase value and a selected power level, wherein the selected frequency is selected from a set of frequencies in a bandwidth of radio frequency electromagnetic waves, the selected phase value is selected from a set of phase values of radio frequency electromagnetic waves, and the selected power level is selected from a set of power levels and identify the resonant modes excited within the enclosed cavity.

[0006] In another aspect, a method of exciting an enclosed cavity with radio frequency radiation includes exciting the enclosed cavity with a selected set of phasors for a set of frequencies; collecting forward and reflected power measurements for the selected set of phasors; determining an efficiency spectrum for the selected set of phasors; identifying the resonant modes of the enclosed cavity based on the computed efficiency spectrum; and classifying foodstuff located within the enclosed cavity based on the identified resonant modes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] In the drawings:

[0008] FIG. 1 is a block diagram of an electromagnetic cooking device with multiple coherent radio frequency feeds in accordance with various aspects described herein.

[0009] FIG. 2 is a block diagram of a radio frequency signal generator of FIG. 1.

[0010] FIG. 3 is a schematic diagram illustrating a high-power radio frequency amplifier coupled to a waveguide in accordance with various aspects described herein.

[0011] FIG. 4 is a cross-sectional diagram illustrating an integrated circulator for use in a high-power radio frequency amplifier in accordance with various aspects described herein.

[0012] FIG. 5 is a top-view diagram illustrating the integrated circulator of FIG. 4.
FIG. 6 is a schematic diagram illustrating a high-power radio frequency amplifier coupled to a waveguide with an integrated measurement system in accordance with various aspects described herein.

FIG. 7 is a schematic diagram illustrating a high-power radio frequency amplifier coupled to a waveguide with an integrated measurement system including a reflectometer in accordance with various aspects described herein.

FIG. 8 is a schematic diagram illustrating a resonant cavity coupled to two radio frequency waveguides in accordance with various aspects described herein.

FIG. 9 is a graphical diagram illustrating efficiency versus frequency for in-phase and anti-phase excitations of the resonant cavity of FIG. 8.

FIG. 10 is a diagram illustrating features of a method of analysis to determine the resonant modes of the cavity in accordance with various aspects described herein.

FIG. 11 is a diagram illustrating features of a method to characterize the resonant modes of the cavity in accordance with various aspects described herein.

FIG. 12 is a schematic diagram illustrating features of a method to locate and classify foodstuff positioned with in a resonant cavity in accordance with various aspects described herein.

FIG. 13 is a flowchart illustrating a method of identifying resonant modes and classifying foodstuff positioned within a resonant cavity in accordance with various aspects described herein.

DETAILED DESCRIPTION

It is to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification are simply exemplary embodiments of the inventive concepts defined in the appended claims. Hence, other physical characteristics relating to the embodiments disclosed herein are not to be considered as limiting, unless the claims expressly state otherwise.

A solid-state radio frequency (RF) cooking appliance heats up and prepares food by introducing electromagnetic radiation into an enclosed cavity. Multiple RF feeds at different locations in the enclosed cavity produce dynamic electromagnetic wave patterns as they radiate. To control and shape of the wave patterns in the enclosed cavity, the multiple RF feeds can radiate waves with separately controlled...
electromagnetic characteristics to maintain coherence (that is, a stationary interference pattern) within the enclosed cavity. For example, each RF feed can transmit a different frequency, phase and/or amplitude with respect to the other feeds. Other electromagnetic characteristics can be common among the RF feeds. For example, each RF feed can transmit at a common but variable frequency. Although the following embodiments are directed to a cooking appliance where RF feeds direct electromagnetic radiation to heat an object in an enclosed cavity, it will be understood that the methods described herein and the inventive concepts derived herefrom are not so limited. The covered concepts and methods are applicable to any RF device where electromagnetic radiation is directed to an enclosed cavity to act on an object inside the cavity. Exemplary devices include ovens, dryers, steamers, and the like.

[0023] FIG. 1 shows a block diagram of an electromagnetic cooking device 10 with multiple coherent RF feeds 26A-D according to one embodiment. As shown in FIG. 1, the electromagnetic cooking device 10 includes a power supply 12, a controller 14, an RF signal generator 16, a human-machine interface 28 and multiple high-power RF amplifiers 18A-D coupled to the multiple RF feeds 26A-D. The multiple RF feeds 26A-D each couple RF power from one of the multiple high-power RF amplifiers 18A-D into an enclosed cavity 20.

[0024] The power supply 12 provides electrical power derived from mains electricity to the controller 14, the RF signal generator 16, the human-machine interface 28 and the multiple high-power RF amplifiers 18A-D. The power supply 12 converts the mains electricity to the required power level of each of the devices it powers. The power supply 12 can deliver a variable output voltage level. For example, the power supply 12 can output a voltage level selectively controlled in 0.5-Volt steps. In this way, the power supply 12 can be configured to typically supply 28 Volts direct current to each of the high-power RF amplifiers 18A-D, but can supply a lower voltage, such as 15 Volts direct current, to decrease an RF output power level by a desired level.

[0025] A controller 14 can be included in the electromagnetic cooking device 10, which can be operably coupled with various components of the electromagnetic cooking device 10 to implement a cooking cycle. The controller 14 can also be operably coupled with a control panel or human-machine interface 28 for receiving user-selected inputs and
communicating information to a user. The human-machine interface 28 can include operational controls such as dials, lights, switches, touch screen elements, and displays enabling a user to input commands, such as a cooking cycle, to the controller 14 and receive information. The user interface 28 can include one or more elements, which can be centralized or dispersed relative to each other. The controller 14 may also select the voltage level supplied by power supply 12.

[0026] The controller 14 can be provided with a memory and a central processing unit (CPU), and can be preferably embodied in a microcontroller. The memory can be used for storing control software that can be executed by the CPU in completing a cooking cycle. For example, the memory can store one or more pre-programmed cooking cycles that can be selected by a user and completed by the electromagnetic cooking device 10. The controller 14 can also receive input from one or more sensors. Non-limiting examples of sensors that can be communicably coupled with the controller 14 include peak level detectors known in the art of RF engineering for measuring RF power levels and temperature sensors for measuring the temperature of the enclosed cavity or one or more of the high-power amplifiers 18A-D.

[0027] Based on the user input provided by the human-machine interface 28 and data including the forward and backward (or reflected) power magnitudes coming from the multiple high-power amplifiers 18A-D (represented in FIG. 1 by the path from each of the high-power amplifiers 18A-D through the RF signal generator 16 to the controller 14), the controller 14 can determine the cooking strategy and calculate the settings for the RF signal generator 16. In this way, one of the main functions of the controller 14 is to actuate the electromagnetic cooking device 10 to instantiate the cooking cycle as initiated by the user. The RF signal generator 16 as described below then can generate multiple RF waveforms, that is, one for each high-power amplifier 18A-D based on the settings indicated by the controller 14.

[0028] The high-power amplifiers 18A-D, each coupled to one of the RF feeds 26A-D, each output a high power RF signal based on a low power RF signal provided by the RF signal generator 16. The low power RF signal input to each of the high-power amplifiers 18A-D can be amplified by transforming the direct current electrical power provided by the power supply 12 into a high power radio frequency signal. In one non-limiting
example, each high-power amplifier 18A-D can be configured to output an RF signal ranging from 50 to 250 Watts. The maximum output wattage for each high-power amplifier can be more or less than 250 Watts depending upon the implementation. Each high-power amplifier 18A-D can include a dummy load to absorb excessive RF reflections.

[0029] The multiple RF feeds 26A-D couple power from the multiple high-power RF amplifiers 18A-D to the enclosed cavity 20. The multiple RF feeds 26A-D can be coupled to the enclosed cavity 20 in spatially separated but fixed physical locations. The multiple RF feeds 26A-D can be implemented via waveguide structures designed for low power loss propagation of RF signals. In one non-limiting example, metallic, rectangular waveguides known in microwave engineering are capable of guiding RF power from a high-power amplifier 18A-D to the enclosed cavity 20 with a power attenuation of approximately 0.03 decibels per meter.

[0030] Additionally, each of the RF feeds 26A-D can include a sensing capability to measure the magnitude of the forward and the backward power levels or phase at the amplifier output. The measured backward power indicates a power level returned to the high-power amplifier 18A-D as a result of an impedance mismatch between the high-power amplifier 18A-D and the enclosed cavity 20. Besides providing feedback to the controller 14 and the RF signal generator 16 to implement, in part, a cooking strategy, the backward power level can indicate excess reflected power that can damage the high-power amplifier 18A-D.

[0031] Along with the determination of the backward power level at each of the high-power amplifiers 18A-D, temperature sensing at the high-power amplifier 18A-D, including at the dummy load, can provide the data necessary to determine if the backward power level has exceeded a predetermined threshold. If the threshold is exceeded, any of the controlling elements in the RF transmission chain including the power supply 12, controller 14, the RF signal generator 16, or the high-power amplifier 18A-D can determine that the high-power amplifier 18A-D can be switched to a lower power level or completely turned off. For example, each high-power amplifier 18A-D can switch itself off automatically if the backward power level or sensed temperature is too high for several milliseconds. Alternatively, the power supply 12 can cut the direct current power supplied to the high-power amplifier 18A-D.
[0032] The enclosed cavity 20 can selectively include subcavities 22A-B by insertion of an optional divider 24 therein. The enclosed cavity 20 can include, on at least one side, a shielded door to allow user access to the interior of the enclosed cavity 20 for placement and retrieval of food or the optional divider 24.

[0033] The transmitted bandwidth of each of the RF feeds 26A-D can include frequencies ranging from 2.4 GHz to 2.5 GHz. The RF feeds 26A-D can be configured to transmit other RF bands. For example, the bandwidth of frequencies between 2.4 GHz and 2.5 GHz is one of several bands that make up the industrial, scientific and medical (ISM) radio bands. The transmission of other RF bands is contemplated and can include non-limiting examples contained in the ISM bands defined by the frequencies: 13.553 MHz to 13.567 MHz, 26.957 MHz to 27.283 MHz, 902 MHz to 928 MHz, 5.725 GHz to 5.875 GHz and 24 GHz to 24.250 GHz.

[0034] Referring now to FIG. 2, a block diagram of the RF signal generator 16 is shown. The RF signal generator 16 includes a frequency generator 30, a phase generator 34 and an amplitude generator 38 sequentially coupled and all under the direction of an RF controller 32. In this way, the actual frequency, phases and amplitudes to be output from the RF signal generator 16 to the high-power amplifiers are programmable through the RF controller 32, preferably implemented as a digital control interface. The RF signal generator 16 can be physically separate from the cooking controller 14 or can be physically mounted onto or integrated into the controller 14. The RF signal generator 16 is preferably implemented as a bespoke integrated circuit.

[0035] As shown in FIG. 2 the RF signal generator 16 outputs four RF channels 40A-D that share a common but variable frequency (e.g. ranging from 2.4 GHz to 2.5 GHz), but are settable in phase and amplitude for each RF channel 40A-D. The configuration described herein is exemplary and should not be considered limiting. For example, the RF signal generator 16 can be configured to output more or less channels and can include the capability to output a unique variable frequency for each of the channels depending upon the implementation.

[0036] As previously described, the RF signal generator 16 can derive power from the power supply 12 and input one or more control signals from the controller 14. Additional inputs can include the forward and backward power levels determined by the high-power
amplifiers 18A-D. Based on these inputs, the RF controller 32 can select a frequency and signal the frequency generator 30 to output a signal indicative of the selected frequency. As represented pictorially in the block representing the frequency generator 30 in FIG. 2, the selected frequency determines a sinusoidal signal whose frequency ranges across a set of discrete frequencies. In one non-limiting example, a selectable bandwidth ranging from 2.4 GHz to 2.5 GHz can be discretized at a resolution of 1 MHz allowing for 101 unique frequency selections.

[0037] After the frequency generator 30, the signal is divided per output channel and directed to the phase generator 34. Each channel can be assigned a distinct phase, that is, the initial angle of a sinusoidal function. As represented pictorially in the block representing the per channel phase generator 36A-D in FIG. 2, the selected phase of the RF signal for a channel can range across a set of discrete angles. In one non-limiting example, a selectable phase (wrapped across half a cycle of oscillation or 180 degrees) can be discretized at a resolution of 10 degrees allowing for 19 unique phase selections per channel.

[0038] Subsequent to the phase generator 34, the RF signal per channel can be directed to the amplitude generator 38. The RF controller 32 can assign each channel (shown in FIG. 2 with a common frequency and distinct phase) to output a distinct amplitude in the channel 40A-D. As represented pictorially in the block representing the per channel amplitude generator in FIG. 2, the selected amplitude of the RF signal can range across a set of discrete amplitudes (or power levels). In one non-limiting example, a selectable amplitude can be discretized at a resolution of 0.5 decibels across a range of 0 to 23 decibels allowing for 47 unique amplitude selections per channel.

[0039] The amplitude of each channel 40A-D can be controlled by one of several methods depending upon the implementation. For example, control of the supply voltage of the amplitude generator 38 for each channel can result in an output amplitude for each channel 40A-D from the RF signal generator 16 that is directly proportional to the desired RF signal output for the respective high-power amplifier 18A-D. Alternatively, the per channel output can be encoded as a pulse-width modulated signal where the amplitude level is encoded by the duty cycle of the pulse-width modulated signal. Yet another alternative is to coordinate the per channel output of the power supply 12 to
vary the supply voltage supplied to each of the high-power amplifiers 18A-D to control the final amplitude of the RF signal transmitted to the enclosed cavity 20.

[0040] As described above, the electromagnetic cooking device 10 can deliver a controlled amount of power at multiple RF feeds 26A-D into the enclosed cavity 20. Further, by maintaining control of the amplitude, frequency and phase of the power delivered from each RF feed 26A-D, the electromagnetic cooking device 10 can coherently control the power delivered into the enclosed cavity 20. Coherent RF sources deliver power in a controlled manner to exploit the interference properties of electromagnetic waves. That is, over a defined area of space and duration of time, coherent RF sources can produce stationary interference patterns such that the electric field is distributed in an additive manner. Consequently, interference patterns can add to create an electromagnetic field distribution that is greater in amplitude than any of the RF sources (i.e. constructive interference) or less than any of the RF sources (i.e. destructive interference).

[0041] The coordination of the RF sources and characterization of the operating environment (i.e. the enclosed cavity and the contents within) can enable coherent control of the electromagnetic cooking and maximize the coupling of RF power with an object in the enclosed cavity 20. Efficient transmission into the operating environment can require calibration of the RF generating procedure. As described above, in an electromagnetic heating system, the power level can be controlled by many components including the voltage output from the power supply 12, the gain on stages of variable gain amplifiers including both the high-power amplifiers 18A-D and the amplitude generator 38, the tuning frequency of the frequency generator 30, etc. Other factors that affect the output power level include the age of the components, inter-component interaction and component temperature.

[0042] Referring now to FIG. 3, a schematic diagram illustrating a high-power amplifier 18 coupled to a waveguide 110 in accordance with various aspects described herein is shown. The high-power amplifier 18 includes one or more amplification stages 100 coupled via a guiding structure 102 to a circulator 104. The circulator 104 is coupled by a guiding structure 106 to a waveguide exciter 108. The high-power amplifier 18 is
electrically coupled to the waveguide 110 by the waveguide exciter 108 and mechanically coupled by an electromagnetic gasket 112.

[0043] The high-power amplifier 18 is configured such that a number of amplification stages 100 are interconnected to amplify a radio frequency signal from the amplifier input to the amplifier output. The amplification stages 100 include one or more transistors configured to convert a small change in input voltage to produce a large change in output voltage. Depending upon the configuration of the circuit, the amplification stages 100 can produce a current gain, a voltage gain or both.

[0044] The output of the amplification stages 100 is coupled to the circulator 104 via a guiding structure 102. The guiding structure 102 can be any electrical connector capable of carrying high-power radio frequency signal including but not limited to a microstrip printed on a dielectric substrate of a printed circuit board. The circulator 104 is a passive multi-port component that transmits radio frequency signals from one port to the next where a port is a point on the circulator 104 for coupling a radio frequency signal from one component to another. In the high-power amplifier 18, the circulator 104 acts as a protective device to isolate the amplification stages 100 from deleterious effects that can occur when a mismatched load reflects power.

[0045] The circulator 104 is coupled to the waveguide exciter 108 via the guiding structure 106. The high-power amplifier 18 is terminated at its output by the waveguide exciter 108. The waveguide exciter 108 converts electromagnetic energy from a first mode suitable for transmission within the high-power amplifier 18 to a second mode suitable for transmission within the waveguide 110. In this way, the waveguide 110 acts as an RF feed 26A-D to convey the amplified electromagnetic signal from the high-power amplifier to the microwave cavity.

[0046] The electromagnetic gasket 112 provides a secure connection between the high-power amplifier 18 and the waveguide 110 and surrounds the portion of the waveguide exciter 108 positioned between the high-power amplifier 18 and the waveguide 110. The electromagnetic gasket 112 can be formed of one or more materials useful for securing the connection between the high-power amplifier 18 and the waveguide 110 and providing electromagnetic shielding at radio frequencies. Such materials can include, but
are not limited to, silicone-based constituents filled with conductive particles such as silver or nickel.

[0047] The provision of the waveguide exciter 108 that terminates the output of the high-power amplifier 18 reduces the electromagnetic losses typically incurred at the junction of microwave devices coupled via conventional connectors. That is, conventional microwave devices are interconnected via coaxial connectors (e.g. BNC or N-type connectors) that incur RF losses due to the additional path lengths for the connectors as well as the losses at the coupling of the coaxial connectors. The electromagnetic gasket 112 augments the efficiency of the waveguide exciter 108 by shielding the waveguide exciter 108 as well as providing the mechanical support of the coupling between the high-power amplifier 18 and the waveguide 110.

[0048] Referring now to FIG. 4, a cross-sectional side view illustrating the circulator 104 in accordance with various aspects described herein is shown. As described above, the circulator 104 is coupled to the output of the amplification stages via the guiding structure 102. The circulator 104 includes a laminate 122 mounted to a metal base plate 120.

[0049] Two ferrite magnets 126, 128 in axial alignment perpendicular to the laminate 122 are secured to the laminate 122 by clips 130. The ferrite magnets 126, 128 can be any shape suitable for the circulator design, including, but not limited to a disk.

[0050] The guiding structure 102 can include a microstrip that is printed on a laminate 122. The laminate 122 is a dielectric substrate that can include any material suitable for the provision of insulating layers of a printed circuit board including, but not limited to, FR-2 material or FR-4 material. The laminate 122 is positioned on the metal base plate 120 that provides mechanical support to the circulator 104. Additionally, the metal base plate 120 acts as a thermal dissipating mass and to spread heat generated by the circulator 104. The metal base plate 120 includes a pocket 124 to house the lower ferrite magnet 128.

[0051] During the manufacturing of the circulator 104, the lower ferrite magnet 128 is placed in the pocket 124 of the metal base plate 120. The laminate 122 and microstrip guiding structure are applied to the metal base plate 120. The upper ferrite magnet 126 is placed above lower ferrite magnet 128 and secured to the laminate 122 by clips 130.
FIG. 5 is a top-view diagram illustrating the integrated circulator of FIG. 4.

As described, the circulator 104 includes, as part of its magnetic circuit, the laminate 122 of a printed circuit board as well as the microstrip guiding structure 102 coupled to the output of the amplification stages (cf. element 100 in FIG. 3). In this way, the circulator 104 does not include input or output pins that require a soldered connection during the manufacturing process. Conventional solder joints can expose the high-power amplifier to reliability issues because the soldering process can result in cold-spots or bad couplings. Therefore, the circulator 104 is not a conventional discrete component soldered in the high-power amplifier. Instead the circulator 104 is directly integrated as a component of the high-power amplifier.

For the output power level at the end of the amplification stages 100 to hit a desired set-point level, the RF signal generator (cf. element 16 in FIG. 1) can rely on feedback in the form of signals indicative of the forward and backward power levels or the relative phases of the radio frequency signals conveyed to the enclosed cavity (cf. element 20 in FIG. 1). Therefore, in addition to the amplifying components for outputting a radio frequency signal that is amplified in power with respect to an input radio frequency signal, conventional high-power amplifiers can include a measuring component that outputs a signal indicative of the radio frequency power transmitted and received by the amplifying component. However, by integrating such a measurement component within the high-power amplifier, the output stage of a high-power amplifier can incur electrical losses that can reduce the power and fidelity of the radio frequency signal output to the radio frequency feed (cf. elements 26A-D in FIG. 1) such as a waveguide.

Referring now to FIG. 6, schematic diagram illustrating a high-power amplifier 18 coupled to a waveguide 110 with an integrated measurement system 150 in accordance with various aspects described herein is shown. The integrated measurement system 150 includes probe antennas 152 coupled to electronic components 154. The probe antennas 152 include portions located within the waveguide 110 that convert radio frequency electromagnetic waves within the waveguide 110 into an analog electric power signal. The probe antennas 152 can be any type of antenna useful for measuring
radio frequency electromagnetic waves within a waveguide, including but not limited to, dipole antennas.

[0056] The electronic components 154 are coupled to the probe antennas 152 and can include an analog-to-digital convertor (ADC) such that the output signal is digital and readily input to a device such as the RF signal generator (cf. element 16 in FIG. 1), controller (cf. element 14 in FIG. 1) or the RF controller (cf. element 32 in FIG. 1). The electronic components 154 can be any component useful for the measurement of radio frequency signals including, but not limited to, radio frequency log power detectors that provide a direct current output voltage that is log-linear with respect to the detected radio frequency power level within the waveguide 110.

[0057] The measurement system can include additional components useful for further characterizing the radio frequency transmissions conveyed through the waveguide 110. Referring now to FIG. 7, a schematic diagram illustrating a high-power radio frequency amplifier 18 coupled to a waveguide 110 with an integrated measurement system 160 that includes a reflectometer 164 in accordance with various aspects described herein is shown. The integrated measurement system 160 includes probe antennas 162 coupled to a reflectometer 164. The probe antennas 162 include portions located within the waveguide 110 that convert radio frequency electromagnetic waves within the waveguide 110 into an analog electric power signal. The probe antennas 162 can be any type of antenna useful for measuring radio frequency electromagnetic waves within a waveguide, including but not limited to, dipole antennas.

[0058] The reflectometer 164 can include any components useful for measuring the phase of a radio frequency signal including, but not limited to, a directional coupler containing matched calibrated detectors or a pair of single-detector couplers oriented so as to measure the electrical power flowing in both directions within the waveguide 110. In this way, the integrated measurement system 160 can characterize the radio frequency transmissions according to power and phase and can be used to form a networked description as embodied in the scattering matrix or S-parameters. In one non-limiting implementation, the reflectometer 164 is a six port reflectometer configured to measure the phase of the forward and backward radio frequency radiation within the waveguide.
The reflectometer 164 is coupled to the probe antennas 162 and can include an analog-to-digital convertor (ADC) such that the output signal indicative of the phase or power of the radio frequency electromagnetic wave within the waveguide 110 or scattering matrix is digital and readily input to a device such as the RF signal generator (cf. element 16 in FIG. 1), controller (cf. element 14 in FIG. 1) or the RF controller (cf. element 32 in FIG. 1).

By characterizing the conveyed radio frequency transmissions according to power and phase measurements or scattering matrix, the electromagnetic cooking device (cf. element 10 in FIG. 1) with solid-state radio frequency sources can precisely excite an enclosed cavity (cf. element 20 in FIG. 1) by controlling the coupling factor of the resonant modes or standing waves that determine the heating pattern therein. That is, a solid-state electromagnetic cooking device can energize desired heating patterns by coupling specific resonant modes to the microwave cavity via the actuation of the radio frequency sources where the heating pattern is determined by the modulus of the resonant mode. The resonant modes are a function of the cavity dimension, food load type, food load placement and excitation condition of the multiple coherent radio frequency sources (e.g. the operating frequency and phase shift between the sources, etc.). The electromagnetic cooking device can be configured to control the solid-state radio frequency sources to select the coupling factor of the resonant modes to energize a specific heating pattern or a sequence of heating patterns over time. The heating patterns related to specific resonant modes can determine the evenness or unevenness of the cooking process. However, because the resonant modes are a function of the food load type and placement, the cavity size and excitation condition, it is not possible to have an a priori knowledge of the resonant modes and their critical frequencies.

Therefore, the electromagnetic cooking device can be configured to determine the resonant modes within an enclosed cavity in-situ. Referring now to FIG. 8, a schematic diagram illustrating a resonant cavity 222 coupled to two RF feeds 226A,B embodied as waveguides in accordance with various aspects described herein is shown. The RF feeds 226A,B couple power from their respective high-power amplifiers (cf. elements 18A,B in FIG. 1) to the enclosed cavity 222. The RF feeds 226A,B can be coupled to the enclosed cavity 222 in spatially separated but fixed physical locations. The RF feeds
226A,B can convey RF transmissions to the enclosed cavity 222 at a selected frequency and phase where the phase shift or difference between the RF transmissions directly relates to the class of symmetry of the coupled resonant mode. For example activating the RF sources in an in-phase relationship (i.e. phase shift = 0°) activates modes of even symmetry while activating the sources in an antiphase relationship (i.e. phase shift = 180°) activates modes of odd symmetry. The symmetries determine the heating patterns in the oven as will be described below.

[0062] In operation, the electromagnetic cooking device determines the set of symmetries (e.g. even or odd) for the resonant modes to be excited within the cavity 222. The electromagnetic cooking device is configured to excite the cavity 222 for a set of operating frequencies and store the efficiency measured for each frequency. The efficiency is determined by the useful power output divided by the total electrical power consumed which can be measured according to the ratio of forward power less the backward power to forward power as in:

$V = \frac{\sum P_{\text{forward}} - \sum P_{\text{backward}}}{\sum P_{\text{forward}}}$

The electromagnetic cooking device is configured to store the efficiency map in memory for the excited classes of symmetries.

[0063] Referring now to FIG. 9, a graphical diagram illustrating efficiency versus frequency for in-phase excitations 228 and antiphase excitations 230 of the resonant cavity is shown. In this non-limiting illustrative example, the electromagnetic cooking device is configured to conduct two sets of excitations for each operating frequency and obtain two efficiency measurements.

[0064] Referring now to FIG. 10, a diagram illustrating features of a method of analysis to determine the resonant modes of the cavity in accordance with various aspects described herein is shown. The electromagnetic cooking device can analyze the recorded map of efficiency (shown for the in-phase excitation 228) by modeling the response as a passband RLC circuit in order to recognize the critical frequencies of the poles (i.e. the resonant frequencies of the resonant modes) that have been excited for the specific class of symmetry. For this purpose, a processor 250 as a physical or logical subcomponent of the controller (cf. element 14 in FIG. 1) or the RF controller (cf. element 32 in FIG. 1) can
be configured to identify local maxima of the efficiency function. The processor 250 can implement any algorithm useful for determining the critical frequencies of the poles of the efficiency map including, but not limited to vector fitting, magnitude vector fitting, etc. In this way, the processor 250 can determine a list of resonant frequencies 252 for each symmetry plane.

Additionally, the processor 250 can determine the quality factor based on the relative bandwidth of each determined pole. The processor 250 can determine the presence of foodstuff located within the cavity based on the estimate of the quality factor. For example, if the processor 250 determines that a selected resonant mode has a low quality factor such as at or below seven, the processor 250 can determine that the portions of the enclosed cavity where the excited mode has a local or global maximum contain foodstuff. Similarly, if the processor 250 determines that a selected resonant mode has a high quality factor such as greater than 1000, the processor can determine that the portions of the enclosed cavity where the excited mode has a local or global maximum do not have foodstuff. The processor 250 can classify the type of foodstuff located within the cavity based on the estimate of the quality factor. For example, frozen food has a quality factor of about 300, water has a quality factor of about 7 and metal objects has a quality factor of about 1000. For each determined pole, the processor 250 can associate a resonant frequency used to excite the mode and a quality factor for determining the type of foodstuff that will be heated by the mode.

Referring now to FIG.11, a diagram illustrating features of a method to characterize the resonant modes of the cavity in accordance with various aspects described herein is shown. Building on the previously described example of an in-phase excitation 228 of the radio frequency feeds 226A,B where a processor of the electromagnetic cooking device determines a set of poles 252 indicative of the resonant modes excitable in the cavity 222, the determined poles 252A-C each correspond to a heating pattern 260A-C within the cavity 222. Recall that the heating pattern is determined by the modulus of the resonant mode. Each heating pattern 260A-C will have a spatial pattern with contours indicative of uniform heating. While depicted in FIG. 11 with a binary set of contours, the actual heating patterns will include many contours indicative of a continuum of heating levels. For ease of understanding, the single contour
level indicates the hottest areas of the heating pattern and demonstrate the even and odd symmetries of the resonant modes.

Referring now to FIG. 12, a schematic diagram illustrating features of a method to locate and classify foodstuff 300A,B positioned within a resonant cavity 222 in accordance with various aspects described herein is shown. Initiating an in-phase excitation, the electromagnetic cooking device can generate a heating pattern 360A in the cavity 222 with an even symmetry where the maximum heating contours 302 do not occur in the center of the cavity 222. Because a large portion 312 of the foodstuff 300A is lying within a minimum of the heating pattern 360A, the cavity reflections are more significant the electromagnetic response from the foodstuff 300A leading to a relatively low efficiency. In contrast, because a large portion 314 of the foodstuff 300B is lying within a maximum of the heating pattern 360B for an antiphase excitation, the cavity reflections are minimized and the efficiency is higher than the efficiency determined during the even symmetry excitation. Therefore, the electromagnetic cooking device can determine if foodstuff is located in the center of the cavity 222 by comparing the efficiencies between the efficiencies between an in-phase excitation and an antiphase excitation. To wit, a higher efficiency with in-phase excitation indicates that foodstuff is not located in the center of the cavity and a higher efficiency with an antiphase excitation indicates the foodstuff is located at the center of the cavity. In this way, the electromagnetic cooking device can be configured to determine the presence of foodstuff positioned in the center of the microwave cavity based on the efficiency of the activated resonant modes of even symmetry or determine the presence of foodstuff positioned remotely from the center of the microwave cavity based on the efficiency of the activated resonant modes of odd symmetry.

Additionally, the processor can be configured to further analyze the quality factors according to the efficiency and symmetry of the resonant modes to detect and locate more than one type of foodstuff in the cavity 222. The processor can be configured to average the quality factors for a subset of the identified resonant modes to classify a portion 310, 314 of a foodstuff 300A, 300B according to its position within the microwave cavity 222. For example, the processor can average the quality factors of the even symmetry modes to determine the type of foodstuff located in a portion 310 of the
foodstuff 300A that intersects with the maximum heating contours 302 of the even
symmetry heating patterns 360A. Similarly, the processor can average the quality factors
of the odd symmetry modes to determine the type of foodstuff located in a portion 314
of the foodstuff 300B that intersects with the maximum heating contours 304 of the odd
symmetry heating patterns 360B.

[0069] Referring now to FIG. 13, a flowchart illustrating a method 400 of identifying
resonant modes and classifying foodstuff positioned within a resonant cavity in
accordance with various aspects described herein is shown. The method 400 includes
steps to: excite the microwave cavity with selected phasors; collect forward and reflected
power measurements for a set of frequencies and phasors; compute efficiency versus
frequency to determine an efficiency spectrum for the selected phasors; identify the
resonant modes of the microwave cavity based on the computed efficiency spectrum and
classify the foodstuff according to the resonant modes and efficiency spectrum.

[0070] At step 402, the electromagnetic cooking device excites the microwave cavity
with selected phasors for a set of operating frequencies. The selected set of phasors can
include in-phase phasors where the RF feeds convey radio frequency signals with no
phase shift and antiphase phasors where the RF feeds convey radio frequency signals
with a phase shift of 180°.

[0071] At step 404, the electromagnetic cooking device by way of an integrated
measurement system can collect forward and backward power measurements in the
waveguides of the RF feeds. Alternatively or additionally, the measurement system can
be configured to measure phase or characterize the radio frequency network according
to the scattering parameters.

[0072] At step 406, the electromagnetic cooking device by way of a processor can
determine the efficiency spectrum for each symmetry of resonant mode. The processor
is configured to determine the efficiency for the operating set of frequencies for each
selected phasor. For example, when the selected set of phasors include the in-phase and
antiphase relationships, the processor can determine an efficiency spectrum for the even
and odd modes.

[0073] At step 408, the electromagnetic cooking device by way of a processor can
identify the resonant modes in the microwave cavity. The processor is configured to
model the cavity as a passband \( L\)\( C \) circuit and determine the center frequency and quality factor for each pole indicative of a resonant mode.

At step 410, the electromagnetic cooking device by way a processor can classify foodstuff within the cavity. The processor can be configured to compare the efficiency between the even and odd symmetry modes to locate the position of foodstuff within the cavity. The processor can be further configured to determine the composition of the foodstuff based on the determined quality factor of the modes. Finally, the processor can be configured to determine the composition and location of portions of the foodstuff by averaging quality factors for subset of the identified resonant modes.

As described above, the method includes steps to determine and classify resonant modes that are activated when the radio frequency sources of an electromagnetic cooking device couple energy into a microwave cavity based on readings of forward and backward power or the phase of travelling waves. The method enables the electromagnetic cooking device to determine the resonant modes based on efficiency measurements of the absorption spectrum for the transmitted frequencies. Further, the method enable the electromagnetic cooking device to characterize the spatial distribution of the resulting heating patterns by the determined resonant modes. Because a resonant mode exists only at a specific discrete frequency, the coupling between the radio frequency sources and the resonant modes is a function of the operating frequency of the radio frequency sources. Additionally, the coupling of the sources with the modes of a resonant cavity is a function of the source excitation, source placement and the phase relationship between the sources. The method enables the electromagnetic cooking device to locate and identify the composition of foodstuff to be cooked within the cavity.

For purposes of this disclosure, the term "coupled" (in all of its forms, couple, coupling, coupled, etc.) generally means the joining of two components (electrical or mechanical) directly or indirectly to one another. Such joining may be stationary in nature or movable in nature. Such joining may be achieved with the two components (electrical or mechanical) and any additional intermediate members being integrally formed as a single unitary body with one another or with the two components. Such
joining may be permanent in nature or may be removable or releasable in nature unless otherwise stated.

[0077] It is also important to note that the construction and arrangement of the elements of the device as shown in the exemplary embodiments is illustrative only. Although only a few embodiments of the present innovations have been described in detail in this disclosure, those skilled in the art who review this disclosure will readily appreciate that many modifications are possible (e.g., variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, mounting arrangements, use of materials, colors, orientations, etc.) without materially departing from the novel teachings and advantages of the subject matter recited. For example, elements shown as integrally formed may be constructed of multiple parts or elements shown as multiple parts may be integrally formed, the operation of the interfaces may be reversed or otherwise varied, the length or width of the structures and/or members or connector or other elements of the system may be varied, the nature or number of adjustment positions provided between the elements may be varied. It should be noted that the elements and/or assemblies of the system may be constructed from any of a wide variety of materials that provide sufficient strength or durability, in any of a wide variety of colors, textures, and combinations. Accordingly, all such modifications are intended to be included within the scope of the present innovations. Other substitutions, modifications, changes, and omissions may be made in the design, operating conditions, and arrangement of the desired and other exemplary embodiments without departing from the spirit of the present innovations.

[0078] It will be understood that any described processes or steps within described processes may be combined with other disclosed processes or steps to form structures within the scope of the present device. The exemplary structures and processes disclosed herein are for illustrative purposes and are not to be construed as limiting.

[0079] It is also to be understood that variations and modifications can be made on the aforementioned structures and methods without departing from the concepts of the present device, and further it is to be understood that such concepts are intended to be covered by the following claims unless these claims by their language expressly state otherwise.
The above description is considered that of the illustrated embodiments only. Modifications of the device will occur to those skilled in the art and to those who make or use the device. Therefore, it is understood that the embodiments shown in the drawings and described above is merely for illustrative purposes and not intended to limit the scope of the device, which is defined by the following claims as interpreted according to the principles of patent law, including the Doctrine of Equivalents.
What is claimed is:

1. An electromagnetic cooking device comprising:
   - an enclosed cavity;
   - a set of radio frequency feeds configured to introduce electromagnetic radiation into the enclosed cavity to heat up and prepare food;
   - a set of high-power radio frequency amplifiers coupled to the set of radio frequency feeds, each high-power amplifier comprising at least one amplifying stage configured to output a signal that is amplified in power with respect to an input radio frequency signal;
   - a signal generator coupled to the set of high-power radio frequency amplifiers for generating the input radio frequency signal; and
   - a controller configured to:
     - cause the signal generator and selected ones of the set of high-power amplifiers to output a radio frequency signal of a selected frequency, a selected phase value and a selected power level, wherein the selected frequency is selected from a set of frequencies in a bandwidth of radio frequency electromagnetic waves, the selected phase value is selected from a set of phase values of radio frequency electromagnetic waves, and the selected power level is selected from a set of power levels; and
     - identify the resonant modes excited within the enclosed cavity.

2. The electromagnetic cooking device of claim 1, wherein the controller is further configured to classify foodstuff positioned within the enclosed cavity according to material composition or location therein.

3. The electromagnetic cooking device of any one of claims 1 and 2, wherein each of the set of radio frequency feeds includes a waveguide coupled at one end to one of the high-power radio frequency amplifiers and coupled at the other end to the enclosed cavity.
4. The electromagnetic cooking device of claim 3, wherein each of the set of radio frequency feeds includes a measurement system configured to output a digital signal indicative of the radio frequency signal conveyed within the waveguide.

5. The electromagnetic cooking device of claim 4, wherein the measurement system includes at least two probe antennas positioned within each waveguide.

6. The electromagnetic cooking device of any one of claims 4 and 5, wherein the measurement system includes a reflectometer configured to measure the phase of the forward and backward radio frequency electromagnetic signals conveyed within each waveguide.

7. The electromagnetic cooking device of any of claims 1-6, wherein each of the high-power amplifiers includes an integrated circulator further comprising:

   a microstrip positioned on a laminate of a printed circuit board configured to receive the output of the at least one amplifying stage;

   a metal base plate positioned beneath the laminate of the printed circuit board;

   a first ferrite magnet positioned within a pocket formed within the metal base plate;

   a second ferrite magnet positioned above and aligned with the first ferrite magnet; and

   one or more clips configured to secure the second magnet above the first ferrite magnet.

8. The electromagnetic cooking device of any one of claims 3-7, wherein each of the high-power amplifiers includes a waveguide exciter with a first portion that terminates the output of the high-power amplifier and a second portion positioned within the corresponding waveguide and the waveguide exciter is configured to convert electromagnetic energy from a first mode suitable for transmission within the high-power amplifier to a second mode suitable for transmission within the waveguide.
9. The electromagnetic cooking device of claim 8, further including an electromagnetic gasket configured to secure the connection between each of the high-power amplifiers and the corresponding waveguide and surround a portion of the waveguide exciter located between the high-power amplifier and the corresponding waveguide.

10. The electromagnetic cooking device of any of claims 1-9, wherein the selected phase value is selected from a set of phasors with an in-phase relationship to activate resonant modes of even symmetry within the enclosed cavity and from a set of phasors with an antiphase relationship to activate resonant modes of odd symmetry within the enclosed cavity.

11. The electromagnetic cooking device of claim 10, wherein the controller is further configured to determine the presence of foodstuff positioned in the center of the enclosed cavity based on at least one of an efficiency and a quality factor of the activated resonant modes of even symmetry or determine the presence of foodstuff positioned remotely from the center of the enclosed cavity based on at least one of an efficiency and a quality factor of the activated resonant modes of odd symmetry.

12. A method of exciting an enclosed cavity with radio frequency radiation, the method comprising:

- exciting the enclosed cavity with a selected set of phasors for a set of frequencies;
- collecting forward and reflected power measurements for the selected set of phasors;
- determining an efficiency spectrum for the selected set of phasors;
- identifying the resonant modes of the enclosed cavity based on the computed efficiency spectrum; and
- classifying foodstuff located within the enclosed cavity based on the identified resonant modes.

13. The method of claim 12, wherein the step of classifying the foodstuff includes identifying the composition of the foodstuff.
14. The method of any of claims 12 and 13, wherein the step of classifying the foodstuff includes determining the position of the foodstuff within the cavity.

15. The method of any of claims 12-14, wherein the step of identifying the resonant modes includes modelling the enclosed cavity as a passband RLC circuit and determining the critical frequencies of the resonant modes that have been excited for a specific class of symmetry.

16. The method of claim 15, further including determining a quality factor of each identified resonant mode.

17. The method of any one of claims 15 and 16, wherein the step of determining the critical frequencies includes a step of vector fitting.

18. The method of any one of claims 15 and 16, further includes averaging the quality factors for a subset of the identified resonant modes to classify at least a portion of the foodstuff according to its position within the enclosed cavity.

19. The method of any of claims 12-18, wherein exciting the enclosed cavity includes selecting the set of phasors with an in-phase relationship to activate resonant modes of even symmetry within the enclosed cavity and selecting the set of phasors with an antiphase relationship to activate resonant modes of odd symmetry within the enclosed cavity.

20. The method of claim 19, further including determining the presence of foodstuff positioned in the center of the enclosed cavity based on the efficiency of the activated resonant modes of even symmetry or determining the presence of foodstuff positioned remotely from the center of the enclosed cavity based on the efficiency of the activated resonant modes of odd symmetry.
Excite the microwave cavity with selected phasors

Collect forward and backward power measurements

Determine efficiency spectrum

Identify resonant modes

Classify foodstuff
This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. □ Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. □ Claims Nos.:
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. □ Claims Nos.: 7-1 1, 15-20
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

This International Searching Authority found multiple inventions in this international application, as follows:

1. □ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. □ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. □ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. □ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

| □ | The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee. |
| □ | The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation. |
| □ | No protest accompanied the payment of additional search fees. |
INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 2016/035727

A. CLASSIFICATION OF SUBJECT MATTER

H05B 6/68 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H05B 6/00-6/74

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatSearch (RUPTO internal), USPTO, PAJ, Esp@cenet, DPWI, EAPATIS, PATENTSCOPE, Information Retrieval System of FTPS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<tbody>
<tr>
<td>X</td>
<td>US 2010/0176121 A1 (PANASONIC CORPORATION) 15.07.2010 (art. 1.5, (0009) - (0179)).</td>
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<tr>
<td>Y</td>
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<td>2-6, 12-14</td>
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<tr>
<td>Y</td>
<td>US 7111247 B2 (LG ELECTRONICS INC.) 19.09.2006, (abstract, fig.6)</td>
<td>2-6, 12-14</td>
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<tr>
<td>Y</td>
<td>RU 2253 193 C2 (SANKT-PETERBURGSKIJ GOSUDARSTVENNYJ UNIVERSITET) 27.05.2005 (claims, fig.3, 6, 7, 9 p.11)</td>
<td>3-4</td>
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<td>Y</td>
<td>FR 2766272 A1 (MOULINEX) 22.01.1999 (abstract)</td>
<td>5-6</td>
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<td>A</td>
<td>GB 2193619 A (APV MAGNETRONICS LIMITED) 10.02.1988</td>
<td>1-6, 12-14</td>
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

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Date of the actual completion of the international search

02 September 2016 (02.09.2016)

Date of mailing the international search report

15 September 2016 (15.09.2016)

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