

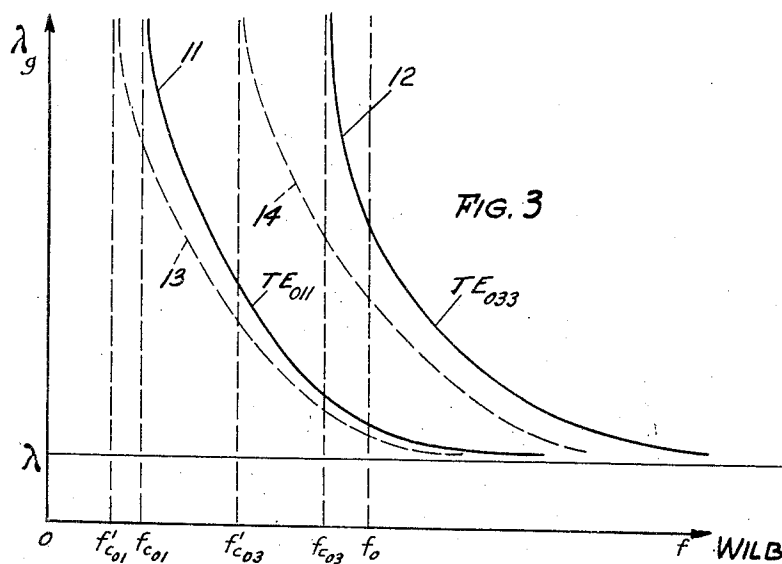
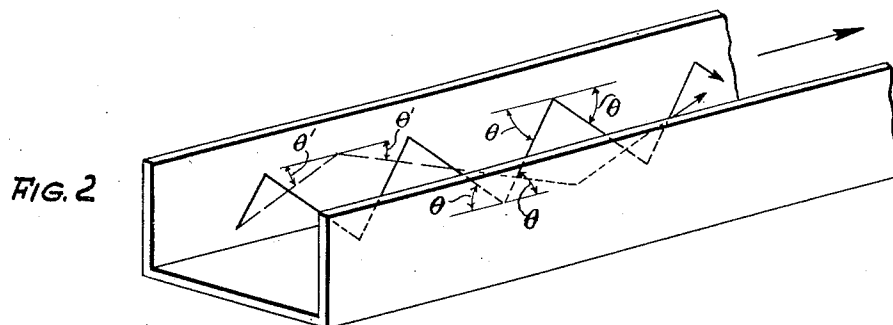
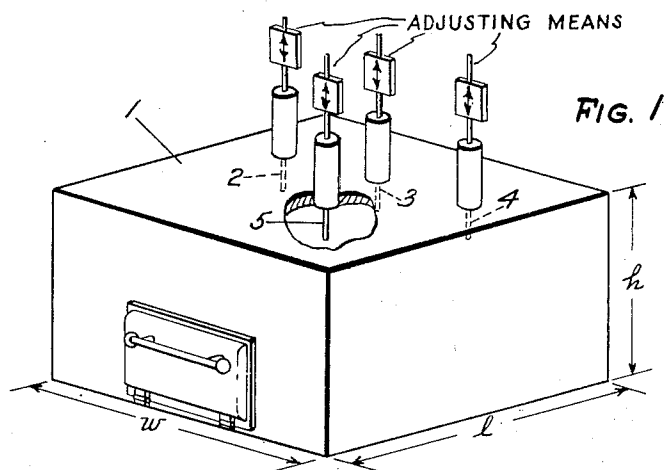
Sept. 18, 1956

W. L. PRITCHARD
MICROWAVE OVENS

2,763,757

Filed Feb. 8, 1952

2 Sheets-Sheet 1



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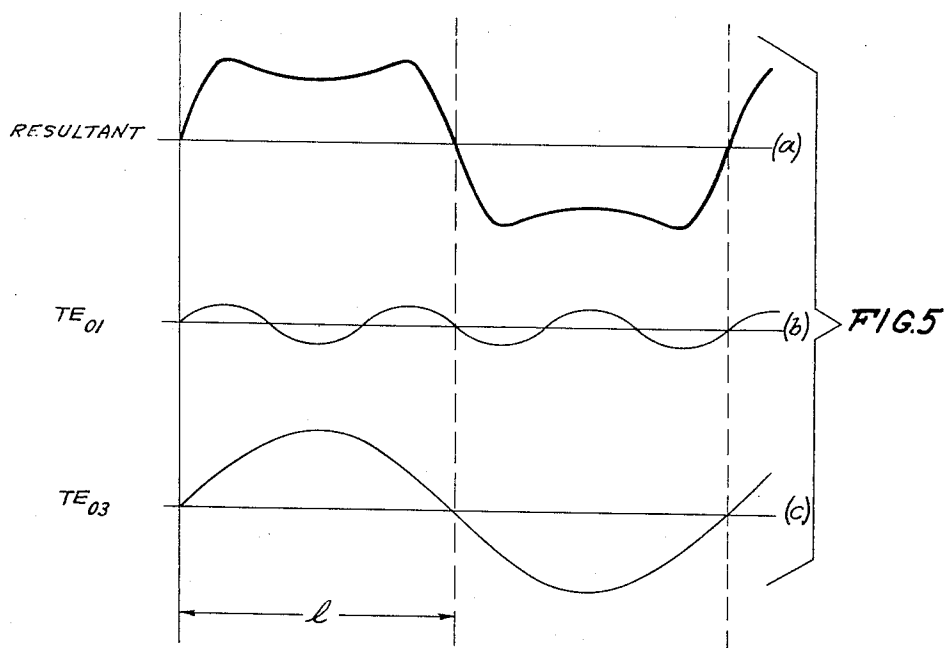
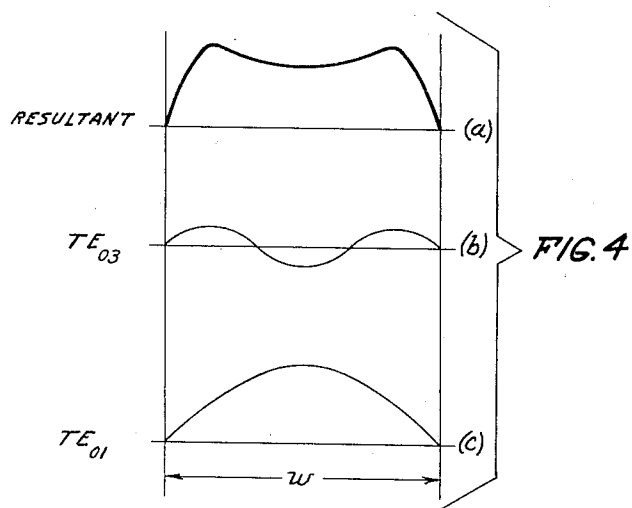
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MICROWAVE OVENS

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7 Claims. (Cl. 219—10.55)

This invention relates to microwave ovens, and more particularly relates to microwave ovens comprising a resonant cavity excited simultaneously in two or more selected modes.

In existing ovens of the type operating at microwave frequencies, substantially uniform heating is achieved by making the oven large compared to a wave length and having it oscillate in a large number of modes simultaneously. To further enhance the operation of the ovens of the prior art, some type of mode stirrer is employed which further perturbs the field within the oven and which results, at least statistically, in uniform heating. Unfortunately, however, this method is unsuitable when the wave length becomes long, since the oven then assumes intolerably large proportions and dissipation of energy within the oven becomes excessive.

In accordance with this invention, substantially uniform heating may be obtained in a comparatively small oven at relatively low frequency. The operating frequency range may be quite large and is limited by the fact that at the higher microwave frequencies the depth of penetration of microwave energy into the object to be cooked or heated is small, while, at lower microwave frequencies, the voltage gradient required will become unduly large.

The oven is constructed in the form of a resonant cavity which is resonant in two or more selected modes simultaneously. These modes are chosen so that the field distribution for each mode is sinusoidal in configuration and corresponds to the terms of the Fourier series. By combining the proper modes and by correlating the amplitudes thereof in the proper manner, a substantially uniform resultant field distribution may be obtained just as by properly combining the harmonics of a sinusoidal wave form, a resultant wave approaching a square wave may be obtained.

The excitation of a cavity or oven in these modes may be obtained by conventional probes inserted in the cavity and fed from a magnetron or other high frequency source of energy by a transmission network, such as a coaxial line or wave guide.

The oven may be excited in several modes since a more nearly uniform distribution of energy in the oven may be obtained as more and more modes are combined. This is analogous to taking more terms of a Fourier series to secure better representation of a desired wave shape. For practical purposes, however, two modes are usually sufficient, and the necessity for a complicated array of probes for excitation in several modes is thereby obviated. These modes may, for example, be the TE₀₁₁ and the TE₀₃₃ modes, with the amplitude of the latter being approximately one-third of the former. The resulting field produced in the resonant cavity type oven by the two modes simultaneously is substantially uniform over approximately seventy per cent of the oven width and length.

In the drawings:

Fig. 1 portrays an embodiment of a microwave oven;

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Fig. 2 is a fragmentary view illustrating the directions taken by elementary TE₀₁ waves as they progress through a wave guide or cavity resonator;

Fig. 3 are curves illustrating certain operating principles of the subject invention;

Fig. 4 graphically illustrates the electric field distribution of the resonator of Fig. 1 as seen through a transverse cross-section; and

Fig. 5 graphically illustrates the electric field distribution in the cavity resonator of Fig. 1 as seen through a cross-section taken in the longitudinal direction.

Numerous modes of oscillation may exist in a cavity resonator, depending upon the cross-section of the resonator and upon the method of exciting the resonator from the energy source. In addition to the fundamental mode of oscillation, there will be found in the resonator other natural modes which may be harmonics of this frequency. The condition for resonance in a given mode in a cavity resonator, which may be treated as a wave guide short circuited at both ends, occurs when a half-guide wave length for the mode concerned is contained an integral number of times in the distance between shorting plates, that is when

$$l = p \frac{\lambda_g}{2} \quad (1)$$

where l is the length of the oven, as shown in Fig. 1 and where p is an integer.

Cavity resonators are essentially wave guides closed at both ends and possessing standing waves. Since the theory applicable to wave guides is generally applicable to cavity resonators, certain operating principles of the cavity resonator type oven will be explained on the basis of wave guide theory.

As is well known, the electric field distribution in the transverse plane in a wave guide for the TE₀₁ mode is sinusoidal and is maximum at the center of the guide and zero at the reflecting surfaces, as shown in Fig. 4(c). The electric field distribution in the same plane for the TE₀₃ mode is also sinusoidal but exhibits three half-wave patterns across the width of the guide, as shown in Fig. 4(b).

It should be noted at this point that the use of two subscripts to describe the given mode is used where the electric field distribution in the transverse plane only is being considered. Modes in cavities usually are designated by a three-number system in which a third small number or subscript signifies the number of half patterns crossed perpendicular to the transverse field. In considering the cavity resonator as a whole, therefore, the use of the three-number system will be employed.

The electric field distribution for the TE₀₁ and TE₀₃ modes is analogous to a fundamental sinusoidal wave and a third harmonic of the fundamental. By combining odd harmonics of a fundamental sinusoidal wave with the fundamental, a resultant wave form is obtained which approaches a square wave having uniform amplitude. The larger the number of harmonics combined with the fundamental, the more closely a square wave is approached. There is, however, a practical limit to the number of modes which can be selectively excited without requiring a complicated feed array. As previously stated, two modes are usually sufficient in practice. The oven therefore may be excited in the TE₀₁ and TE₀₃ modes. The transverse distribution of the electric field in the cavity is shown in Fig. 4. The electric field distribution for the TE₀₁ mode is shown in Fig. 4(c) and the electric field distribution for the TE₀₃ mode is shown in Fig. 4(b). The resultant transverse electric field distribution in the oven may be obtained by adding

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algebraically the curves of Figs. 4(b) and 4(c) and is shown in Fig. 4(a).

The group velocity or velocity of propagation of R. F. energy in the wave guide, V_g , is slower than the velocity in free space owing to the fact that the wave is reflected from wall to wall, as shown in Fig. 2. Since

$$V_p = f\lambda_g$$

where V_p is the phase velocity and is greater than the physical constant C , the wave length within the guide λ_g is always greater than its free space value λ .

The angle θ which determines the direction of propagation of the TE₀₁ wave as it is reflected by the walls of the guide is given by

$$\theta = \tan^{-1} \frac{1}{\sqrt{\left(\frac{f}{f_c}\right)^2 - 1}} \quad (2)$$

If the cutoff frequency f_c and operating frequency f are equal, $\tan \theta$ equals infinity and θ becomes equal to ninety degrees. In this condition, there is obviously no propagation since the wave bounces back and forth between the side walls in a direction perpendicular to the walls. If the cutoff frequency differs from the operating frequency, there is a progression of the waves in the direction of propagation indicated by the arrow in Fig. 2. In Fig. 2, the paths of the TE₀₁ waves corresponding to cutoff frequencies which are removed from the operating frequency by different amounts are shown. The solid line corresponds to the condition in which the cutoff frequency is relatively close to the operating frequency while the dashed line represents the condition in which the cutoff frequency is relatively far from the operating frequency.

To summarize, as the frequency becomes lower, the guide wave length increases since the angle θ becomes larger and there are more reflections from the wave guide walls for a given amount of forward travel of the waves.

The cutoff wave length for a rectangular cavity across section w , h is given by

$$\lambda_c = \frac{2}{\sqrt{\left(\frac{m}{w}\right)^2 + \left(\frac{n}{h}\right)^2}} \quad (3)$$

where m is the number of half-period space variations in the intensity of the electric field encountered in going across the wider dimension w of the guide and n is the number of transverse half-wave patterns existing along the short dimension h of the guide.

From Equation 3 it is evident that the cutoff wave length and consequently the cutoff frequency are dependent upon the mode; that is, each mode has its own guide wave length for a given operating frequency. For a TE₀₁ or TE₀₃ mode, $n=0$ and Equation 3 simplifies to

$$\lambda_c = \frac{2}{\sqrt{\left(\frac{m}{w}\right)^2}} = \frac{2w}{m} \quad (4)$$

From Equation 4 it is apparent that the TE₀₃ mode is closer to the cutoff frequency of the guide than the TE₀₁ mode so that its guide wave length in the direction of propagation, as shown by the dashed line of Fig. 2, is longer than that of the TE₀₁ mode, shown in Fig. 2 as a solid line.

Fig. 3 illustrates graphically the manner in which the guide wave length for a given mode may be varied by changing the dimension w of the cavity resonator (guide). Curves 11-14 show the manner in which guide wave length varies with frequency for the TE₀₁ and TE₀₃ modes. The guide wave length varies from infinity at the cutoff frequency f_c to the wave length of free space at infinite frequency. For example, curve 13 indicates that for a cutoff frequency f'_{c01} , the guide wave length varies from infinity at the cutoff frequency f'_{c01} , to λ at infinite frequency. These curves are thus asymptotic

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to the axes corresponding to cutoff frequency f_c and free space wave length λ . Since

$$f_c = \frac{c}{\lambda_c} \quad (5)$$

where c is the velocity of propagation of electromagnetic energy and

$$\lambda_c = \frac{2w}{m}$$

from Equation 4, therefore

$$f_c = \frac{cm}{2w} \quad (6)$$

Since c is a constant and m is constant for any given mode, it is obvious that the cutoff frequency is inversely proportional to the dimension w . For a given operating frequency f , it is possible to change the dimension w so that the cutoff frequency for the TE₀₁ and TE₀₃ modes are shifted from f'_{c01} and f'_{c03} , respectively, to f_{c01} and f_{c03} , respectively. The curves 11 and 12 illustrate the condition at which, for a given operating frequency f_0 , the ratio between the guide wave lengths for the TE₀₃ and TE₀₁ modes is three.

In order to obtain the desired uniform distribution of energy in the resonator by excitation in the TE₀₁ and TE₀₃ modes, the guide wave lengths for the two modes are made an integral multiple of one another; in this case, the guide wave length for the TE₀₃ mode is made equal to three times the guide wave length for the TE₀₁ mode.

The guide wave length for any mode in a wave guide of any cross-section is

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{\lambda_c}\right)^2}} \quad (7)$$

where λ is the free space wave length at the operating frequency and λ_c is the cutoff frequency of the guide.

The above equation is valid provided the value of λ_c corresponds to the mode and cross-section being used.

From Equation 4, $\lambda = 2w$ for the TE₀₁ mode while, for the TE₀₃ mode,

$$\lambda_c = \frac{2w}{3}$$

The relationship between the guide wave lengths for the two modes is

$$\frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{2w}\right)^2}} = \frac{3\lambda}{\sqrt{1 - \left(\frac{\lambda}{2w}\right)^2}} \quad (8)$$

Squaring each side of Equation 8

$$\frac{\lambda^2}{1 - \left(\frac{3\lambda}{2w}\right)^2} = \frac{9\lambda^2}{1 - \left(\frac{\lambda}{2w}\right)^2} \quad (9)$$

Dividing Equation 9 by λ^2 and clearing of principal fractions

$$1 - \left(\frac{\lambda}{2w}\right)^2 = 9 - 9\left(\frac{3\lambda}{2w}\right)^2 \quad (10)$$

Rearranging terms, Equation 10 may be written

$$\frac{\lambda}{w} = \sqrt{\frac{32}{80}} \quad (11)$$

Solving for w ,

$$w = \frac{\lambda}{\sqrt{4}} = 1.58\lambda \quad (12)$$

Since the cross-sectional dimension w controls the guide wave length along the direction of propagation, the value of w as derived from Equation 12 makes possible a longitudinal field distribution as shown in Fig. 5, where

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the longitudinal electric field distribution for the TE₀₁₁ mode is as shown in Fig. 5(b) and the distribution for the TE₀₃₃ mode as shown in Fig. 5(c). The resultant electric field distribution, as shown in Fig. 5(a), is seen to be substantially uniform. Since the resultant field distribution is periodic, it is obvious that the minimum length l may be made one-half the guide wave length for the TE₀₃₃ mode. Since the value of w is now known, the length l may be given by

$$l = 1/2 \frac{\lambda}{\sqrt{1 - \left(\frac{3\lambda}{2w}\right)^2}} \quad (13)$$

Since the cutoff wave length is independent of the h dimension, the height of the cavity is not critical and may be made any convenient value. The height, however, should preferably be less than half the width w to avoid the possibility of setting up spurious higher modes in the cavity.

The uniformity of distribution of energy in the oven will depend partially upon the relative amplitudes of the TE₀₁₁ and TE₀₃₃ modes. Since the field distribution for each mode may be assumed to be sinusoidal, the Fourier series is applicable for determining the resultant field distribution obtained by combining the field distributions of each mode. The Fourier series is of the form

$$f(x) = A_1 \sin x + A_3 \sin 3x + \dots + A_n \sin nx \quad (14)$$

For the purposes of the invention only the first two terms need be considered. The values of coefficients A_1 and A_3 will partially determine the configuration of the waveform. The Fourier series for a square wave has term amplitudes inversely proportional to n , that is, $A_1 = 1$, $A_3 = 1/3$, etc.

The transverse distribution in the cavity is shown in Fig. 4 and is inherent from the fact that the cavity is excited in the TE₀₁₁ and TE₀₃₃ modes. The resultant field distribution in both transverse and longitudinal directions is substantially uniform, as shown in Figs. 4 and 5. As previously stated, the resultant field distribution in both directions may be made still more nearly uniform by exciting in more than two modes. This is analogous to taking more terms of the Fourier series of Equation 14. For example, by exciting the oven in the TE₀₁₁, TE₀₃₃ and TE₀₅₅ modes, the heating of the oven would be more nearly even than that resulting from excitation of the oven in just two modes.

The manner of excitation of the oven is shown in Fig. 1. To excite the oven 1 in the TE₀₃₃ mode, three probes 2, 3 and 4 are inserted in the top of the oven. The probes are connected to a source of microwave energy (not shown), such as a magnetron, by means of coaxial lines or any form of transmission means, such as a wave guide. The end probes 2 and 4 are excited 180 degrees out of time phase with the center probe 3. A single probe 5 is required for excitation in TE₀₁₁ mode and is preferably located at a distance

$$\frac{w}{2}$$

from each of the side walls of the oven. The amplitude of each mode depends upon the location of the probes in the oven and upon the depth to which the probes are inserted therein. The probes may be made readily adjustable so that the depth of penetration into the cavity may be varied. The adjusting means are shown in Fig. 1 of the drawing.

The cavity must be resonant at the frequency of the magnetron or other source of microwave energy. This condition may be accomplished either by coupling energy from the cavity to derive an error signal for automatic frequency control of the microwave source or by merely permitting the cavity to pull the magnetron onto the desired frequency.

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This invention is not limited to the particular details of construction, materials and processes described, as many equivalents will suggest themselves to those skilled in the art. It is accordingly desired that the appended claims be given a broad interpretation commensurate with the scope of the invention within the art.

What is claimed is:

1. In combination, a source of microwave energy operating at a predetermined frequency, a microwave oven whose boundaries define a cavity resonator resonant at least in the TE₀₁₁ and TE₀₃₃ modes, first means connected to said source for exciting said oven in said TE₀₁₁ mode, second means connected to said source for exciting said oven in said TE₀₃₃ mode with an amplitude substantially one-third that of said TE₀₁₁ mode, said modes combining to provide substantially uniform heating within said oven.

2. In combination, a source of microwave energy operating at a predetermined frequency, a microwave oven whose boundaries define a cavity resonator resonant in the TE₀₁₁ and TE₀₃₃ modes, first and second means connected to said source for exciting said oven in said TE₀₁₁ and TE₀₃₃ modes, respectively, said selected modes and amplitudes thereof corresponding to the first few odd terms of a Fourier series, said modes combining to provide a substantially square wave distribution of energy along at least two dimensions of said oven.

3. In combination, a source of microwave energy operating at a predetermined frequency, a microwave oven whose boundaries define a cavity resonator resonant in a plurality of selected harmonically related modes of the form TE_{hwl} where h equals zero and l and w are equal odd integers, means connected to said source for exciting said oven simultaneously in said selected modes, means including said exciting means for correlating the amplitude of the field corresponding to each mode substantially proportional to the reciprocal of the integers w and l for that mode.

4. In combination, a source of microwave energy operating at a predetermined frequency, a microwave oven whose boundaries define a cavity resonator resonant in a plurality of selected harmonically related modes of the form TE_{hwl} where h equals zero and l and w are equal odd integers, means connected to said source for exciting said oven simultaneously in said selected modes whose fields combine to produce a resultant longitudinal and transverse field in the oven which is substantially uniform, means including said exciting means for effecting an adjustment of the amplitude of the field corresponding to each mode which is substantially proportional to the reciprocal of the integers w and l for that mode.

5. In combination, a source of microwave energy operating at a predetermined frequency, a microwave oven capable of producing substantially uniform heating whose boundaries define a substantially rectangular resonant cavity having width w , length l , and height h , means connected to said source for exciting said oven in at least two selected modes of the form TE_{hwl} where w and l are odd integers of equal magnitude and h equals zero, the width w of said cavity being such that a half wave length for each of said modes is contained an integral number of times along dimension l , and means including said means for exciting for adjusting the amplitude of the field corresponding to each mode substantially proportional to the reciprocal of the integers w and l for that mode.

6. In combination, a source of microwave energy operating at a predetermined frequency, a microwave oven capable of producing substantially uniform heating whose boundaries define a substantially rectangular resonant cavity having width w , length l , and height h , a plurality of probes connected to said source and inserted in said oven for exciting said oven in at least two selected modes of the form TE_{hwl} where w and l are odd integers of equal magnitude and h equals zero, the width w of said

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cavity being such that a half wave length for each of said modes is contained an integral number of times along dimension l , and said probes being adjustable within said oven for adjusting the amplitude of the field corresponding to each mode substantially proportional to the reciprocal of w for that mode.

7. In combination, a single source of microwave energy operating at a predetermined frequency, a microwave oven whose boundaries define a resonant cavity having width w , length l , and h , and resonant in a plurality of selected harmonically related modes of the form TE_{hwl} 10 where h equals zero and w and l are odd integers, means connected to said source and adapted to excite said oven simultaneously in said selected modes whose fields combine to produce a resultant longitudinal and transverse 15 field in the oven which is substantially uniform, means

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including said exciting means for effecting an adjustment of the amplitude of the field corresponding to each mode, said selected modes and the magnitude of said amplitude variations corresponding to the first few odd terms of a Fourier series.

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