Feb. 19, 1952 N. R. WILD **2,586,754**

RADIO-FREQUENCY SYSTEM

Filed Nov. 16, 1946 3 Sheets-Sheet 1

FIG. 1

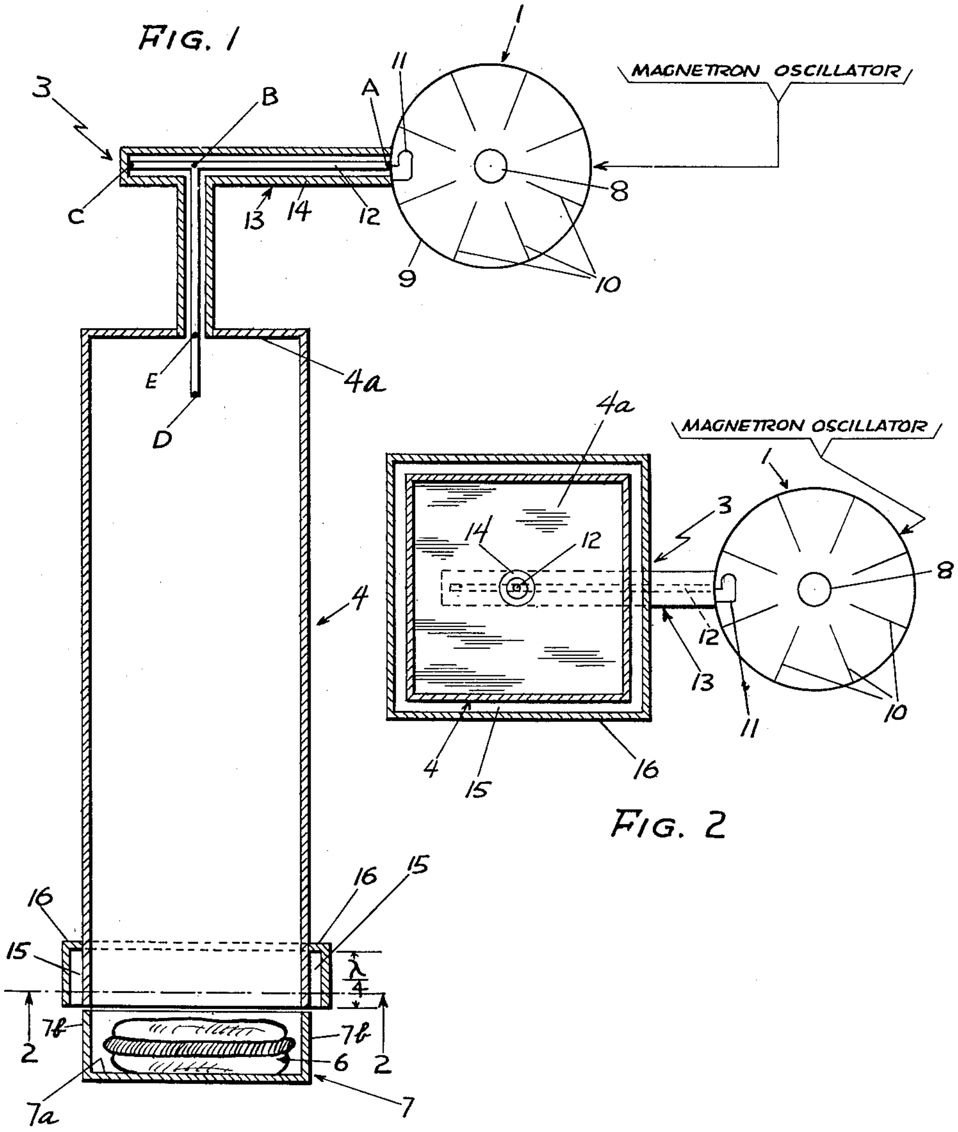

FIG. 2

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Feb. 19, 1952 N. R. WILD 2,586,754

RADIO-FREQUENCY SYSTEM

Filed Nov. 16, 1946 3 Sheets-Sheet 2

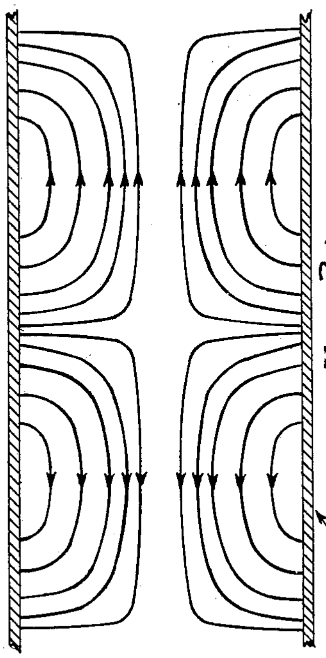

FIG. 3A

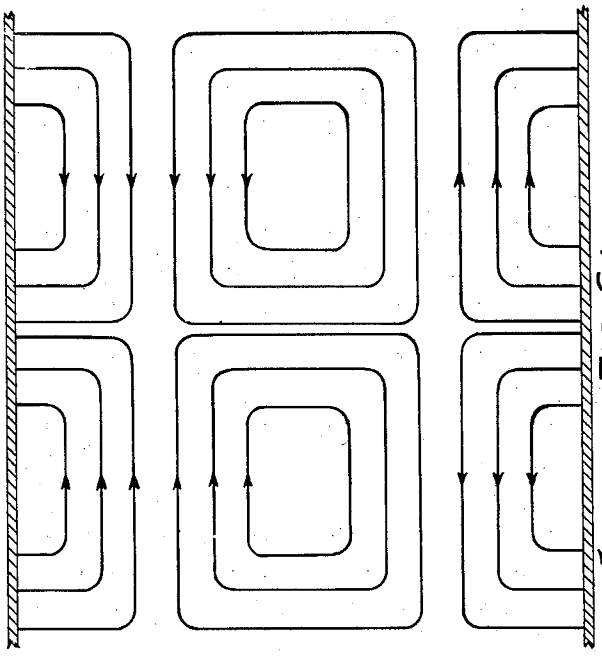

FIG. 6A

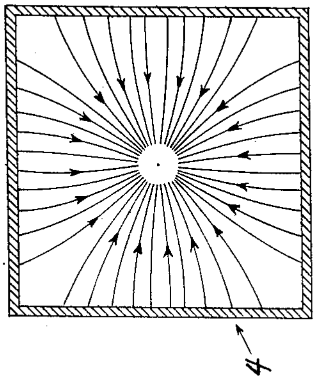

FIG. 3

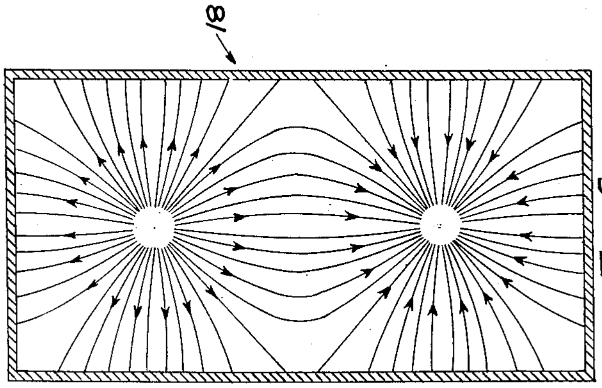

FIG. 6

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Feb. 19, 1952 N. R. WILD 2,586,754

RADIO-FREQUENCY SYSTEM

Filed Nov. 16, 1946 3 Sheets-Sheet 3

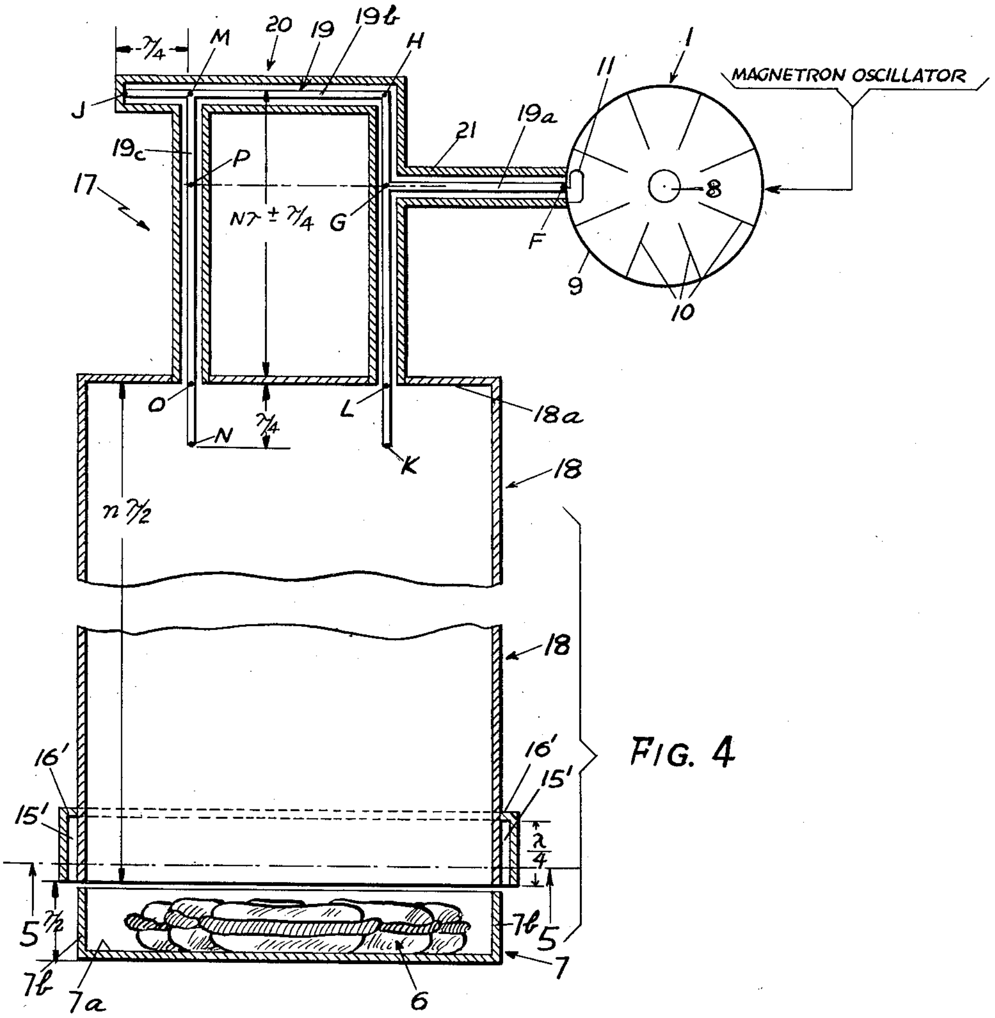

FIG. 4

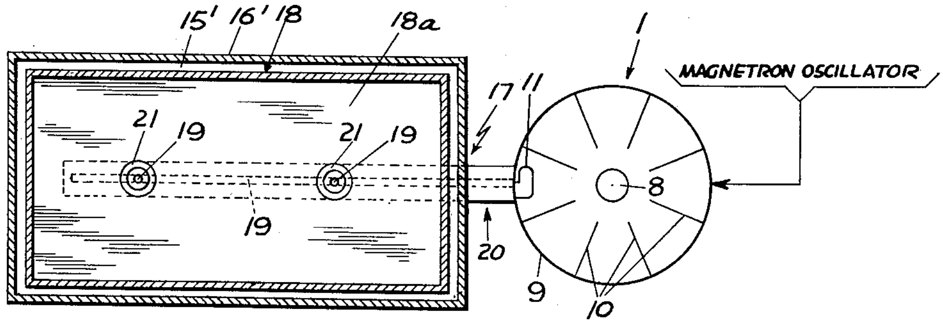

FIG. 5

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UNITED STATES PATENT OFFICE

2,586,754

RADIO-FREQUENCY SYSTEM

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Application November 16, 1946, Serial No. 710,339

2 Claims. (Cl. 178—44)

This invention relates to a radio-frequency system, and more particularly to a microwave transmission system useful for the heating or cooking of foods.

An object of this invention is to devise a microwave cooker which will uniformly heat or cook food.

Another object is to devise a microwave transmission system by the use of which the source of microwave energy, which may for example be an oscillator of the so-called magnetron type, is maintained at a point of favorable phase in the standing wave system of the transmission line, throughout rather large variations in the standing wave ratio of said line.

A further object is to devise a transmission system by the use of which a rather large area of food may be uniformly heated from a single source of microwave energy.

A still further object is to prevent leakage of microwave energy over the edge of the mouth of the horn, which horn is used to transmit energy from the source to the food to be cooked, thereby eliminating the possibility of the feed-over of energy from one horn to another, when two horns, each fed by a separate source of energy, are running side by side.

An additional object is to reduce the standing wave ratio in a microwave transmission and radiation system.

Still another object is to maintain the magnetron at a point of favorable phase in the standing wave system of the feed line, irrespective of wide variations in the characteristics of the object being heated.

The foregoing and other objects of the invention will be best understood from the following description of exemplifications thereof, reference being had to the accompanying drawings, wherein:

Fig. 1 is a central longitudinal cross-section through a microwave energy transmission system according to my invention;

Fig. 2 is a view taken on line **2**—**2** of Fig. 1;

Figs. 3 and 3A are a plot of the electric field intensity in the horn of Fig. 1;

Fig. 4 is a central longitudinal cross-section through a modified transmission system;

Fig. 5 is a view taken on line **5**—**5** of Fig. 4; and

Figs. 6 and 6A are a plot of the electric field intensity in the horn of Fig.4.

Referring, now, to the drawings, and more particularly to Figs. 1 and 2 thereof, a magnetron oscillator **1** is adapted to supply microwave energy, by means of a radio-frequency transmission system **3**, to a hollow waveguide or horn **4** which is substantially closed at its upper end and open at its lower end; the energy is radiated from the open end of said horn onto the food **6** or other substance to be heated, which is positioned below horn **4** by means of a suitable container **7**, to be later described.

Magnetron **1** is conventional and is schematically represented as consisting of a cathode **8** surrounded by a hollow anode structure **9**, which includes a plurality of radially-disposed anode vanes **10** which divide the interior of the anode structure into a plurality of cavities or chambers.

As is well known, such a device can be constructed and operated to produce a rather large amount of radio-frequency power in the microwave region of the frequency spectrum, and may be operated to produce continuous oscillations if desired. The output frequency of such a device depends mainly on the geometrical configuration thereof.

As an example, this device **1** may be operated to produce an energy output having a frequency on the order of 3000 megacycles, said output being coupled to system **3** by means of a coupling loop **11** formed on one end of the inner conductor **12** of a coaxial line **13**; the loop **11** is positioned in one of the cavities provided between adjacent vanes **10**.

One end of loop **11** is connected to the inner conductor **12** of coaxial line **13**, while the other end thereof is connected to the outer conductor **14** of said line. Conductor **12** extends straight from point A (at the coupling loop) for a suitable distance, determined as set forth hereinafter, to point B. In order to support the inner metallic conductor **12** in outer metallic conductor **14**, said inner conductor is extended a distance of an odd number of quarter-wavelengths (at the operating frequency of magnetron **1**) beyond point B, to point C, and is at said latter point firmly connected, mechanically and electrically, to a solid disk which is integral with outer conductor **14**. In other words, the quarter-wavelength stub B—C supports inner conductor **12** of the coaxial line.

In order to supply energy to the horn or waveguide **4**, conductor **12** makes a 90° turn at point B and extends to point D, where said conductor ends. As is more clearly shown in Fig. 2, hollow elongated metallic waveguide **4** is substantially square in cross section; the dimensions of this waveguide will be set out more in detail hereinafter. Horn **4** is a square hollow prism which is entirely open at one end and is substantially closed at its opposite end, as at **4***a*. A circular aperture, of sufficient size for the mounting therein of conductor **14**, is centered at the point of intersection of the diagonals of the square closed end face of horn **4**, and point E of conductor **12**, which is in the same horizontal plane as is the inner face of the closed end of horn **4**, is spaced a distance of approximately $\lambda/4$ from point D; as a result, portion DE of conductor **12** serves as a quarter-wavelength probe or exciting rod for guide **4**. The section AC of the line may be termed the main transmission line, the section BD being termed a branch transmission line.

I have found that excitation of the waveguide **4** in the transverse magnetic ($TM_{m,n}$) mode produces a very even voltage gradient over the bottom or mouth of the horn **4**. Element **4** may be termed either a waveguide or a horn, since it propagates a field therealong as does a waveguide, and also radiates energy from its open end, as does a horn. If an even voltage gradient is produced over the mouth of the horn, a plate of frozen food **6** placed adjacent thereto will heat evenly over the entire surface of the food. As a general rule, foods which are over $\lambda/8$ in length are heated, by microwave energy, partly by induction heating (caused by the H or magnetic lines) and partly by dielectric heating (caused by the E or electric lines). Therefore, in order to heat the food evenly, both the E and H lines should be substantially uniform over the mouth of the horn.

Now referring to Figs. 3 and 3A, a plot of the electric field intensity for this type of wave, with $m=1$ and $n=1$ (known as a $TM_{1,1}$ wave) is shown. Fig. 3 represents a transverse cross-section through the horn, while Fig. 3A represents a side sectional view (a section parallel to the side of the horn and passing through the center of the horn). As represented in Fig. 3, excitation in this mode produces a radial pattern of E lines substantially uniformly over the mouth of the horn. Although the H lines are not shown in these figures, it will be remembered that these lines are everywhere at right angles to the E lines; it should therefore be apparent that the H lines will consist of a plurality of substantially equally-spaced concentric curves. It will therefore be seen that very uniform heating of the food will be produced if the $TM_{m,n}$ mode is utilized. This is contrasted with the conventional transverse electric modes (for example, those designated as $TE_{0,1}$ and $TE_{0,2}$) which produce concentrated E lines in the center of the horn, making alternate hot and cold spots in the food being heated by them.

It may be seen, from Figs. 3 and 3A, that there is a small hole present in the center of the horn with the $TM_{1,1}$ mode. In the drawing, the hole is greatly exaggerated in size for purposes of clarity. This hole must be reduced in size as much as possible, so as not to produce a cold spot in the food. By dimensioning the cross-section of the waveguide **4** to make its cutoff angular frequency as close to the operating frequency of the magnetron **1** as possible, the two vertically-spaced fields shown in Fig. 3A will be squeezed together, thereby narrowing down the hole. It has been found that, for the $TM_{1,1}$ mode, a horn 3.25'' square will give a cutoff wavelength of 11.57 cm. Such a horn will squeeze the hole down pretty well, and, if the nominal operating frequency of the source is 3000 mc. (10 cm.), will provide a reasonable safety factor and also, by virtue of being square, will produce an even radial E pattern as shown in Fig. 3.

Excitation of the guide **4** by exciting rod DE, which is substantially $\lambda/4$ in length and whose center line is collinear with the longitudinal center line of said guide, will produce therein waves of the desired $TM_{1,1}$ type.

Container **7** is made entirely of metal and is constructed to have a wave-reflecting bottom surface **7***a* on which the food **6** rests, spaced a distance of $\lambda/2$ (measured in the guide) from the mouth of the horn **4**. The side walls **7***b* of the container are arranged to enclose substantially the same cross-sectional area as that of horn **4**. These walls enclose the food **6** substantially completely, so that no microwave energy can escape at the sides thereof; therefore substantially all of the power has to dissipate itself in the food, as will be more fully explained hereinafter.

Surrounding all four sides of the horn **4**, at the mouth thereof, is a channel **15** which opens downwardly (that is, it opens toward the mouth of the horn), this channel being provided, for example, by a metallic member **16**, of inverted L-shape, which has its shorter leg firmly bonded to the outer surface of horn **4**. The channel **15** is substantially $\lambda/4$ deep (measured in the guide), for a reason which will appear hereinafter. The width of the channel **15** is somewhat exaggerated in the drawing, for purposes of clarity.

The length of part BE of the branch portion BD of conductor **12** is designed to make the distance from point E to point C (via point B) an integral number of half-wavelengths.

Since the coaxial line **12** is short-circuited at point C, there is an extreme impedance mismatch at this point, so that waves are reflected at said point. The short-circuit at point C acts as a very low impedance, so that a voltage node (an E_{min} in the standing wave system) exists at this point. At point B, which is an odd number of quarter-wavelengths away from point C, this E_{min} reflects a voltage loop (an E_{max} in the standing wave system), since in any system of standing waves, loops are spaced $\lambda/4$ from nodes. Therefore, at point B, due to reflections from point C, we have an E_{max} point.

At this point we will consider what happens in the transmission system when the horn **4** is designed to have a length (in the guide) of an integral number of half-wavelengths (an even number of quarter-wavelengths), with food **6** placed between the reflecting surface **7***a* and the horn **4**; it will be recalled that the surface **7***a* is spaced a distance of $\lambda/2$ from the mouth of the horn **4**.

Wave energy which propagates down the horn (this energy can be propagated because its frequency is above the cutoff angular frequency of the horn) suffers a very small reflection at the mouth of the horn, due to the slight discontinuity thereat, equivalent to a small impedance mismatch; this produces essentially an E_{min} at this point due to the discontinuity or space between the horn and the upper end of container **7**, which space extends entirely around the horn. Energy which impinges upon the upper surface of the food **6** experiences a very slight reflection, also, due to the small impedance mismatch at this point; this energy is in phase or only very slightly out of phase with the energy reflected at the horn mouth because of the close positioning of this upper surface to the mouth of the horn. The great bulk of the energy passes through the food

6, suffering partial attenuation therein which serves to heat the food.

The unattenuated portion of the energy impinges on reflecting surface 7a, being reflected thereby because of the impedance mismatch at this point. Since the impedance of said surface is very low, said surface being a short-circuit between side walls 7b, an E_{min} is established at this point. The energy reflected at surface 7a passes through body 6 a second time and is again partially attenuated thereby, the remaining unattenuated energy proceeding toward the end 4a of the horn and, together with the energy reflected at the mouth of the horn, setting up a system of standing waves in the horn 4. Since the mouth of the horn is spaced a distance of $\lambda/2$ from surface 7a, the energy reflected from said surface will be in phase with that reflected from the mouth of the horn.

The end 4a of the horn "looks," to the reflected wave, like a short-circuiting plate with a small hole in its center, thus in effect "looking" like a low impedance to the reflected wave but like a high impedance to any component of the reflected wave trying to enter the coaxial feed line; the smaller the hole is, the higher such impedance will be. As a result, most of the reflected wave energy does not go down the coaxial feed line, but is reflected by the short-circuiting plate 4a toward the food 6, to be further attenuated thereby, resulting in further heating of the food.

It is, therefore, desirable to make the hole in the upper end 4a of the horn as small as possible, in order to reduce the amount of reflected energy which couples with the coaxial feed line, thereby both reducing the standing wave ratio in the feed line and also utilizing the output energy of the magnetron more efficiently to heat the food. The space between inner conductor 12 and outer conductor 14 of the coaxial line should therefore be made as small as possible, consistent with other considerations which may limit the minimum size of the outer conductor 14.

The closed end surface 4a of the horn 4 is, as stated above, a short-circuiting plate, which has a low impedance. Therefore an E_{min} will be established at this surface, since a short circuit is equivalent to an E_{min} for a standing wave system; this E_{min} is consistent with the fact that the horn is an integral number of half-wavelengths long, making an integral number of half-wavelengths from the E_{min} at reflecting surface 7a to the end 4a of the horn. The low impedance of the short-circuiting plate 4a, which is the closed end of the horn, is reflected at the hole in the center thereof, so that, for waves reflected from horn end 4a which enter the coaxial feed line through said hole, a voltage node or E_{min} is also established at point E, which is in the same horizontal plane as the inner surface of end 4a of the horn.

Since the distance from point E to point C (via point B) is an integral number of half-wavelengths, and since the distance from point C to point B is preferably an odd number of quarter-wavelengths, the distance from point E to point B must necessarily be an odd number of quarter-wavelengths. This means that, if an E_{min} is established at point E, the reflected waves travelling along the coaxial line will establish an E_{max} at point B. It has previously been established that the reflected waves from point C establish an E_{max} at point B.

It will therefore be seen that the reflected waves from the three locations 7a, 4a, and C are all in phase at point B, since all the reflected waves establish E_{max}'s or voltage nodes at said point. Since all of these reflections are in phase, a rather high standing wave ratio is produced in the feed line. This means that the feed line becomes a very highly reactive or very high-Q circuit.

There is a complete short-circuit at point C, and there is substantially a complete short-circuit for reflected waves at horn end 4a, both of these short-circuits being exposed and unimpeded in effectiveness by any energy-absorbing object. As will be seen, the reflecting surface 7a, although it is a short-circuit also, is masked in effectiveness by the presence of the load 6. As a result of these characteristics, there is a rather high standing wave ratio in the line 13 substantially independently of reflections from surface 7a, so that the line 13 is a high-Q circuit even in the absence of such reflections; in effect, therefore, the reflected energy from the two locations C and 4a is what determines and holds fixed the phase at point B. Therefore, the phase in the coaxial line is substantially independent of what goes on at the lower end of the horn; wide variations in the characteristics of the food being heated do not noticeably interfere with the phase of the standing waves in the feed line. Stated in another way, this system has very great phase stability, the phase in the coaxial line remaining substantially constant throughout wide variations in the standing wave ratio.

If the voltage standing wave ratio be plotted against frequency for the above-described design, in which the horn has a length of an integral number of half-wave lengths, we obtain a curve in which the standing wave ratio is rather low over a very wide frequency range, being within reasonable limits over as broad a range as 60 mcs. on each side of a nominal operating frequency of 3000 mc. If the system is designed so that the reflections from the three locations 7a, 4a, and C are not quite in phase, there will be some cancellation, thereby reducing the standing wave ratio and broadening the "hollow" in the curve of voltage standing wave ratio vs. frequency. The voltage standing wave ratio is reduced in the region of the nominal operating frequency because, at this frequency, the horn 4 is the proper length to provide a very efficient reflecting surface or very low impedance at the bottom plate 4a. In this region the standing wave ratio may reach a value on the order of 1.8:1.

It is known that a magnetron will operate most favorably, that is, its operation will be more stable over a wide range of standing wave ratios, when the phase of the feed line at the tube output has a certain optimum value, which value will be different for different types of tubes. By establishing a known and constant value of phase at point B of the feed line (which value may be an E_{max} in my invention, as defined above), it is possible to match the tube 1 to the line, so that the phase of the tube with respect to the line may be put at a value which is favorable for the tube. To accomplish this matching, it is only necessary, the phase at point B being known, to make the distance AB such as to place point B, and therefore also the tube 1, at the desired phase angle. Since the phase at point B remains substantially fixed during operation of the system, the phase at point A will remain substantially at the optimum value.

Even though no food is placed in container **7** and all of the power is reflected from reflector **7a** or from a metal object accidentally left in said container, the magnetron is protected from damage by standing waves. This is so because of the low voltage standing wave ratio (due to the small hole in plate **4a**) and also because of the fact that the phase in the feed line remains fixed throughout large variations in the standing wave ratio, which phase stability, as stated above, is favorable for the magnetron.

If the distance AB is made an odd number of quarter-wave lengths, the magnetron **1** will always be at an E_{min}, since the point B (the coaxial junction) is an E_{max} regardless of the standing wave ratio in the feed line. Now, as the standing wave ratio increases, the higher the peaks of the reactive voltage become, but since the tube is at or near an E_{min}, the lower the relative reactive voltage placed on the tube becomes.

As explained above, the coaxial feed line **13** is a very high-Q circuit, and this circuit, by its geometrical configuration, is tuned to a certain definite frequency. The magnetron **1** also includes a tuned circuit. It is well known that, when two tuned circuits which are slightly mismatched are operating in parallel, the one which has the higher value of Q

$$\left(Q=\frac{\omega L}{R}\right)$$

will tend to take control and will exert an electrical force which tends to "pull" the other circuit into resonance at the proper frequency. Due to the fact that the standing wave ratio in the feed line increases on either side of the nominal operating frequency, which is the frequency to which the magnetron is tuned, the Q of the feed line increases as the actual operating frequency varies from the frequency to which the magnetron is tuned. When the actual operating frequency varies from the frequency to which the magnetron is tuned, the Q of the feed line may go higher than that of the magnetron. As a result, the feed line **13** in such case will tend to take control over the resonant circuit of the magnetron **1**, exerting a force, which, if the magnetron is not operating at the proper frequency, tends to pull the magnetron tube into operation at the proper frequency, which is the frequency to which the magnetron is nominally tuned. Thus there is provided an automatic frequency control.

Although it has not been shown in Figs. 1–2, as a practical matter it is desirable, when using a square horn **4** with a single exciting rod, to use a pair of similar horns placed side by side, each horn being fed by a separate magnetron. This is desirable in order to provide a larger cooking area. When two horns are used side by side, leakage over the edge of the mouths of the horns must be kept at a minimum so that wave energy from one horn will not feed down the other horn in an opposite direction to the incident energy, thereby producing high reactive potentials (equivalent to a very high standing wave ratio). In order to prevent such leakage, a short circuit, which is provided by the closed end of channel **15**, is placed a distance of $\lambda/4$ down from the mouth of the horn **4**; this short circuit surrounds all four sides of the horn, as shown in Fig. 2. This short circuit, or low impedance, reflects an open circuit or high impedance $\lambda/4$ away (at the edge of the horn), so that no wave energy can spill over onto the outside of the horn or into an adjacent horn.

It is within the scope of this invention to devise a system in which the horn **4** has another length than that involved in the preceding discussion, this other length being an odd multiple of $\lambda/4$ (in the horn). We will now consider the action of such a modified system.

With such a system, waves propagate from the end **4a** of the horn toward and through the food **6**, being partially absorbed thereby, as before, reaching the reflecting surface **7a**. Due to the short-circuiting effect or low impedance of surface **7a**, an E_{min} for the standing wave system (which is set up because of reflected waves) would tend to be established at said reflecting surface and therefore also at the mouth of the horn, due to the fact that said mouth is $\lambda/2$ away from said surface.

In order for a standing wave system to be set up in the horn **4**, with an E_{min} at the mouth of the horn and with a horn which is an odd number of quarter-wavelengths long, there would have to be an E_{max} at the end **4a** of the horn. However, because horn end **4a** is a short-circuiting plate, there must be an E_{min} at end **4a**, due to the fact that, for standing wave systems, an open circuit corresponds to an E_{max} and a short circuit to an E_{min}. It is therefore apparent that an impossible or inconsistent situation results in the horn for the existence of standing waves therein. Of course, due to the fact that there is a hole in the horn end or plate **4a**, said plate is not a complete short-circuit, so that some waves are reflected back toward horn end **4a** to set up some standing waves in the horn, but this percentage of waves is very, very low, because of the very small area of the hole as compared to that of the plate **4a**.

In other words, if a low impedance **7a** is placed at the mouth of the horn **4**, the reflected wave set up by this low impedance "looks" at the short-circuiting plate **4a** at the bottom of the horn and "sees" an E_{min} where there should be an E_{max} (due to the length of the horn). This makes the reflected wave see a very high impedance looking down the horn. In fact the impedance looking down the horn is substantially infinite, and would be infinite but for the relatively small hole in plate **4a**. The waves unabsorbed by the food **6** and reflected from surface **7a**, since they "see" a substantially infinite impedance looking down the horn **4**, are constrained to either pass out through the gap between the mouth of the horn and the top of container **7**, or return to the food **6**. Said gap is an open circuit which has, therefore, a very high impedance, so that the reflected waves do not appreciably pass therethrough. The food **6** has a much lower impedance than either the horn or the gap, so that substantially all of the reflected wave energy passes and repasses through food **6** until said energy is completely absorbed, thereby producing a maximum heating effect in said food. In the event that container **7** is empty, the energy passes out the gap between the container and the horn, and also is used in heating the walls of the horn.

Due to the fact that the reflected wave "sees" a high impedance looking down the horn **4**, the standing wave ratio in the coaxial feed line **13** is reduced rather than being raised slightly, as it is when the horn is an even number of quarter-wavelengths long, as described previously. There is a substantial cancellation of reflected wave energy with a horn which is an odd number of quarter-wavelengths long, as explained above, so that, in the region of the operating frequency, the voltage standing wave ratio may reach a value on the order of 1.2:1. The standing wave ratio in a system of this kind is low over a rather wide frequency range, being within reasonable limits over as broad a range as 45 mc. on each side of a nominal operating frequency of 3000 mc.

Since the standing wave ratio in the feed line with a horn of this length is not as high as with a horn which is an even number of quarter-wavelengths long, the Q of the coaxial feed line is not as high as in the first-described horn design. This can also be seen from the fact that reflections from surface **7a** are substantially eliminated from the feed line; therefore reflected wave energies from only the two locations E and C are the energies which are in phase at point B in the feed line **13**, and the energies which determine the phase at point A in said feed line. However, the Q in the coaxial feed line is still quite high, due to the presence of the excellent short-circuits at points C and E, and the reflected energy from these two points is what determines and holds fixed the phase at point B. Therefore, the advantages of phase stability in the feed line, irrespective of different foods **6**, are obtainable with this latter horn design as well as with the first-described horn design.

To recapitulate, the designer may make a choice between a low standing wave ratio over a very broad frequency range and a very high-Q circuit (obtainable with a horn an even number of quarter-wavelengths, or an integral number of half-wavelengths, long), and a lower standing wave ratio over a somewhat narrower frequency range and a somewhat lower-Q circuit (obtainable with a horn an odd number of quarter-wavelengths long). In both designs, the advantages of maintaining the magnetron at the point of most favorable phase, and the frequency-pulling effect of a high-Q feed line circuit, are obtained, as well as the uniform heating of the food (because of the uniform field pattern) and the efficient utilization of the energy in heating of the food (due to the very small percentage of the reflected waves which find their way back to the feed line).

By properly dimensioning the length of the horn, it is possible to have the same horn operate as an even quarter-wavelength horn (as described in the first horn design) at one limit of the range of frequencies over which different magnetrons vary, and as an odd quarter-wavelength horn (as described in the second horn design) at the other limit of said frequency range.

It will be recalled that the cross-sectional dimensions of the horn **4** are such that the cutoff frequency thereof is as close to the magnetron operating frequency as possible, in order to narrow down the hole in the center of the Fig. 3 "E" pattern. The said cross-sectional dimensions of the horn are varied to give a characteristic impedance for the horn which matches the characteristic impedance of the coaxial line. A complete impedance match cannot be obtained in this manner because of the limits imposed on the cross-sectional dimensions of the horn by considerations of horn cutoff frequency; however, as close a match as possible is obtained in this manner and the impedance mismatch then yet remaining is eliminated by varying slightly the length DE of the probe or exciting rod, from its nominal λ/4 length.

If it is desired to use a single magnetron and one horn rather than two magnetrons and two horns, the structure shown in Figs. 4–5 may be utilized. Referring, now, to Figs. 4–5, in which elements the same as those of Figs. 1–2 are denoted by the same reference numerals, a magnetron oscillator **1** is adapted to supply microwave energy, by means of a radio-frequency transmission system **17**, to a hollow waveguide or horn **18** which is substantially closed at its upper end and open at its lower end; the energy is radiated from the open end of said horn onto the food **6** or other substance to be heated, which is positioned below horn **18** by means of container **7**.

The microwave energy output of magnetron **1** is coupled to system **17** by means of a coupling loop **11** formed on one end of a first section **19a** of the inner conductor **19** of a coaxial feed line **20**; the loop **11** is positioned in one of the cavities provided between adjacent vanes **10** of the magnetron.

One end of loop **11** is connected to the inner conductor **19** of coaxial line **20**, as stated, while the other end thereof is connected to the outer conductor **21** of said line. Section **19a** of the conductor **19** extends straight from point F, at coupling loop **11**, for a suitable distance to point G. At point G the conductor **19** makes a right angle or 90° turn, away from horn **18**, extending a suitable distance in this new direction to point H, at which point another 90° turn is made, away from magnetron **1**, to provide another section **19b** of inner conductor **19**. At the opposite end J of section **19b** from point H, in order to support the inner metallic conductor **19** in outer metallic conductor **21**, said inner conductor is firmly connected, mechanically and electrically, to a solid disk which is integral with outer conductor **21**.

The linear portion GH of inner conductor **19** is extended beyond point G, toward and into horn **18** through a circular aperture provided therein which is of suitable size to accommodate the outer conductor **21** of the coaxial line **20**, to point K, the outer conductor **21** being terminated flush with the inner surface of the closed end **18a** of horn **18**. The distance from point L, which is in the same horizontal plane as the inner surface of horn end **18a**, to point K is approximately λ/4, λ being the wavelength of the output energy of magnetron **1**, the length KL of conductor **19** providing a quarter-wavelength exciting rod whose axis extends parallel with the longitudinal center line of horn **18**.

Measuring back, along line JH, a distance of an odd number of quarter-wavelengths from point J, there is established point M. A branch section **19c** of conductor **19** extends, at right angles to section **19b** and therefore parallel to section HK, toward horn or waveguide **18**. A second circular aperture, of sufficient size for the mounting therein of conductor **21**, is provided in horn end **18a**, said second aperture being aligned with section **19c** of the conductor **19**. Section **19c** extends, for a distance MN which is equal to the distance HK, toward and into horn **18** through said second aperture which accommodates the outer conductor **21** of the coaxial line **20**, the outer conductor **21** being again terminated flush with the inner surface of the closed end **18a** of horn **18**. Point O is in the same horizontal plane as the inner surface of horn end **18a**, and the distance NO, like the distance KL, is approximately λ/4; portion NO provides a second exciting rod whose axis is parallel to the longitudinal center line of horn **18**. Point P is located, along section **19c**, in the same horizontal plane as point G and section **19a** of the feed line. The sections FG and HMJ of the line together may be termed the main transmission line sections, PON and GLK being termed branch transmission lines and sections MP and HG being termed stubs or stub lines.

As shown in Fig. 5, the waveguide or horn **18** is rectangular in cross-section, and may have, or example, twice the cross-sectional area of the guide **4** of Fig. 1 for the same magnetron operating frequency. The two spaced apertures in end wall **18***a* are aligned with each other along the longer dimensions of the rectangle and are both located centrally of the shorter dimension of said rectangle. The center of each aperture is preferably spaced a distance of one-fourth the longer dimension from its adjacent (short) side of the rectangle, thus spacing the two aperture center lines apart a distance of one-half the longer dimension of the rectangle.

The portion GHMP of conductor **19** is made an odd number of half-wavelengths long. Therefore, since the length GK of conductor **19** is equal to the length PN, the incident energy appearing at probe tip K will be 180° out of phase with that appearing at probe tip N. Since the patterns radiated by the two probes are 180° apart, and since the probes are parallel to the longitudinal axis of the guide **18**, waves of the $TM_{1,2}$ type are set up in said guide.

Now referring to Figs. 6 and 6A, a plot of the electric field intensity for the $TM_{1,2}$ wave is shown. Fig. 6 represents a transverse cross-section through the horn, while Fig. 6A represents a side sectional view (a section parallel to the side of the horn and passing through the center of the horn). As represented in Fig. 6, excitation in this mode produces a double radial pattern of E lines which is substantially uniform or even over the mouth of the horn. Although the H field lines are not shown in these figures, it will be apparent that the pattern of such lines is also substantially uniform over the mouth of the horn. As a result, very uniform heating of the food **6** will be produced if this $TM_{1,2}$ mode is utilized.

It will be seen that, with the $TM_{1,2}$ system, the same pattern will be produced and the same area will be heated as in the $TM_{1,1}$ system using two magnetrons and two horns, but the $TM_{1,2}$ system requires only a single magnetron and a single horn.

It may be seen, from Figs. 6 and 6A, that there are two small holes present in the horn with the $TM_{1,2}$ mode. In the drawing, the holes are greatly exaggerated in size for purposes of clarity. By dimensioning the cross-section of the horn **18** to make its cutoff angular frequency as close to the operating frequency of the magnetron **1** as possible, the lines shown in Fig. 6A will be squeezed together, thereby narrowing down the holes. It has been found that, for the $TM_{1,2}$ mode, a rectangular horn having a cross-section of 6.5″ x 3.25″ will give a cutoff wavelength of 11.57 cm., which will narrow the holes pretty well and at the same time provide a reasonable safety factor if the nominal operating wavelength of the source is 10 cms.

As in the Figs. 1–2 embodiment, the cross-sectional dimensions of the horn **18** are varied to give a characteristic impedance for the horn which matches the characteristic impedance of the coaxial line. This variation can be made only within limits imposed by considerations of horn cutoff frequency which arise as explained above; however, the impedance mismatch which cannot be remedied by such variation is eliminated by varying slightly the lengths of the exciting rods KL and NO.

As explained above, the distance GHMP is made equal to an odd number of half-wavelengths, so that the patterns radiated by the two exciting rods are 180° apart in phase. The distance JMPO is made an integral number of half-wavelengths, and the distance JMHGL is also made an integral number of half-wavelengths. It is apparent that, for physical reasons, distance distance JMHGL must be greater than distance JMHGL must be greater than distance JMPO. For reasons that will appear hereinafter, the distance LG is made an odd number of quarter-wavelengths. It has been found that, if the distance LG is to be made an odd number of quarter-wavelengths, if the distance PMHG is to be an odd number of half-wavelengths, and if the distance JMHGL is greater than the distance JMPO, then when OPMJ is an odd number of half-wavelengths, JMHGL must be an even number of half-wavelengths, and when OPMJ is an even number of half-wavelengths, JMHGL must be an odd number of half-wavelengths.

With the distances PMHG, JMPO, JMHGL, and JM (which is a quarter-wavelength or an odd number of quarter-wavelengths) being known or designed in accordance with the above enumeration, the remaining distances, such as MH, GH, GL, etc., may be readily calculated.

In this embodiment, as in the embodiment of Figs. 1–2, the food **6** is placed in container **7** adjacent the mouth of the horn **18**, the container having a metallic reflecting surface **7***a* at the bottom thereof.

Also, surrounding all four sides of the horn **18**, at the mouth thereof, is a channel **15′** which opens toward the mouth of the horn, this channel being provided by the metallic member **16′** of L-shape, having its shorter leg firmly attached to the outer surface of horn **18**. Channel **15′**, like channel **15**, is substantially λ/4 deep, and functions in exactly the same way to prevent leakage of energy over the lip of the horn. The width of channel **15′** is exaggerated in the drawing, for purposes of clarity.

As in the Fig. 1 embodiment, the horn **18** may have a length which is either an odd number of quarter-wavelengths or an even number of quarter-wavelengths (an integral number of half-wavelengths), both of these lengths being determined in accordance with the wavelength in the guide or horn, which wavelength is somewhat different from the wavelength in free space.

In operation, the phasing, with the exception of the excitation of the two exciting rods 180° out of phase, works out exactly the same as with the $TM_{1,1}$ horn previously described. First assuming a horn which is an even number of quarter-wavelengths, or an integral number of half-wavelengths, long, a small amount of the incident wave energy propagating down guide **18** reflected from the upper surface of the food, and a small amount is also reflected from the mouth of the horn, due to the discontinuity at this point.

The wave energy which is unattenuated by food **6** after passing therethrough impinges upon reflecting surface **7***a* and is reflected thereby. At this short-circuiting surface **7***a*, an E_{min} is established. This reflected energy, which as before will be in phase with the energy reflected from the mouth of the horn, proceeds toward the end **18***a* of the horn and sets up a system of standing waves in said horn.

Horn end **18***a* "looks" to the reflected wave like a short-circuiting plate with two small holes therein, thus in effect "looking" like a low impedance to the reflected wave but like a high impedance to any component of the reflected wave trying to enter either of the two holes for the coaxial feed line; the smaller such holes are, the higher such impedance will be. As a result, most of the reflected wave energy does not go down the coaxial feed line, but is reflected by horn end plate **18**_a_ toward the food **6**, to be further attenuated thereby.

Although there are two holes in plate **18**_a_, as contrasted to only one hole in plate **4**_a_, plate **18**_a_ is much larger in total area than is plate **4**_a_, so that the amount of reflected energy which couples with feed line **20** is quite small, since the area of the holes in plate **18**_a_ is still small as compared to the total area of said plate.

An E_{min} is established at short-circuiting plate **18**_a_, this being consistent with the fact that there is an E_{min} at surface **7**_a_ and with the distance from surface **7**_a_ to plate **18**_a_, which distance is an integral number of half-wavelengths. In the same manner as before, voltage nodes or E_{min}'s are also set up at points O and L, which are in the same horizontal plane as the inner surface of horn end **18**_a_.

As before, due to the short-circuit at point J, an E_{min} is established at said point, and, since point M is spaced a distance of an odd number of quarter-wavelengths from point J, the waves reflected from point J establish an E_{max} at point M. Since the distance JMPO is an integral number of half-wavelengths, and since the distance JM is an odd number of quarter-wavelengths, the distance OPM is an odd number of quarter-wavelengths. Therefore, the waves reflected from point O also tend to establish an E_{max} at point M, and such reflections are therefore in phase at point M with those from point J.

The distance MHG is an integral number of half-wavelengths, as may readily be seen by computation. Therefore, the reflections from points J and O will tend to establish an E_{max} at point G. Since the distance LG is an odd number of quarter-wavelengths and since an E_{min} is established at point L, as described above, the reflections from point L will also tend to establish an E_{max} at point G.

It will therefore been seen that the reflections from points O, J, and L are all in phase at point G, establishing an E_{max} at point G. Due to the complete short-circuit at point J and to the substantially complete short-circuit for reflected waves at horn end **18**_a_, the reflected energy from these two locations is in effect what determines and holds fixed the phase in the feed line **20** at point G substantially independently of what goes on in the lower (food) end of the horn. This system has great phase stability, due to the rather high standing wave ratio in the feed line (points O, J, L, and **7**_a_ being tied together in phase) and the consequent high-Q of the line.

By establishing a known and constant value of phase at point G of the feed line (which value may, for example, be an E_{max}), the distance GF may be made such as to put the magnetron **1** at whatever phase angle is desired for most favorable operation of the magnetron.

As in the Fig. 1 embodiment, the advantages of a rather low standing wave ratio over a broad frequency range and a fixed-phase, high-Q feed line are obtained, but in the Fig. 4 embodiment a rather large cooking area is obtained with a single magnetron and horn.

If horn **18** is an odd number of quarter-wavelengths long, the phasing and operation are similar to that explained in detail above in connection with Fig. 1, the phasing being as above with E_{min}'s at points O, L, and J. In this case an E_{max} is established and fixed at point G due to the length dimensions of the parts of the feed line and the consequent inphase reflections from the points O, J, and L at point G, although in this case, of course, the standing wave ratio and the Q of the line are both somewhat lower than in the case of the multiple-half-wavelength horn, due to the substantially infinite impedance presented to reflected waves by horn wall **18**_a_ as a consequence of the length of the horn.

Here, also, the advantages of a very low standing wave ratio over a rather broad frequency range and a fixed-phase, rather high-Q feed line are also obtained.

Of course, it is to be understood that this invention is not limited to the particular details as described above, 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 this invention within the art.

What is claimed is:

1. A microwave energy transmission system, comprising a source of microwave energy, a transmission line of U-shape with two extra arms extending substantially parallel to the base of the U, one of said extra arms ending at and intersecting one of the legs of the U intermediate the ends thereof and the center line of said one extra arm lying in a horizontal plane which divides each of the legs of the U into a stub line and a branch line, the stub line of each leg being adjacent to and intersecting the base of the U, the free end of said one extra arm being connected to said source, the other of said extra arms ending at and intersecting the base of the U and being short-circuited at its free end, the lengths of the two stub lines plus the length of the base of the U being an odd number of half-wavelengths at the frequency of said microwave energy, the length of said other extra arm being an odd number of quarter-wavelengths, and a hollow waveguide having a longitudinal axis, said branches extending into said guide at one end thereof parallel to said axis to serve as exciting rods for said guide, the lengths of the portions of each branch between the stub ends of the same and said one end of said guide being an odd number of quarter-wavelengths long at said frequency.

2. A microwave energy transmission system, comprising a source of microwave energy, a transmission line of U-shape with two extra arms extending substantially parallel to the base of the U, one of said extra arms ending at and intersecting one of the legs of the U intermediate the ends thereof and the center line of said one extra arm lying in a horizontal plane which divides each of the legs of the U into a stub line and a branch line, the stub line of each leg being adjacent to and intersecting the base of the U, the free end of said one extra arm being connected to said source, the other of said extra arms ending at and intersecting the base of the U and being short-circuited at its free end, the lengths of the two stub lines plus the length of the base of the U being an odd number of half-wavelengths at the frequency of said microwave energy, the length of said other extra arm being an odd number of quarter-wavelengths,

and a hollow waveguide having a closed end and a longitudinal axis, said branches extending into said guide through the closed end thereof parallel to said axis to serve as exciting rods for said guide, the lengths of the portions of each branch between the stub ends of the same and said closed end of said guide being an odd number of quarter-wavelengths, the distance along the leg of the U nearer said other extra arm, from a point lying in the plane of the closed end of said guide, to the short-circuited end of said other extra arm, being an integral multiple of a half-wavelength, and the distance along the other leg of the U and along the base of the U, from a point lying in the plane of the closed end of said guide, to the short-circuited end of said other extra arm, being an integral multiple of a half-wavelength long at said frequency.

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REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
2,259,318	Mouromtseff	Oct. 14, 1941
2,281,550	Barrow	May 5, 1942
2,283,935	King	May 26, 1942
2,297,512	Baeyer	Sept. 29, 1942
2,373,233	Dow	Apr. 10, 1945
2,392,511	Thompson et al.	Jan. 8, 1946
2,398,606	Wang	Apr. 16, 1946
2,404,797	Hansen	July 30, 1946
2,407,318	Mieher	Sept. 10, 1946
2,407,690	Southworth	Sept. 17, 1946
2,408,032	Beck	Sept. 24, 1946
2,427,094	Evans	Sept. 9, 1947
2,497,670	Hanson et al.	Feb. 14, 1950
2,500,752	Hanson et al.	Mar. 14, 1950
2,513,205	Roberts	June 27, 1950
2,537,182	Bertrand	Jan. 9, 1951

OTHER REFERENCES

"Practical Analysis of Ultra High Frequency Transmission Lines, Resonant Sections, Resonant Cavities, Wave Guides," by J. R. Meagher and H. J. Markley, August 1943, R. C. A. Service Company, Inc., Camden, N. J.

Steel, vol. 117, No. 20, November 12, 1945, page 92.