FIG. 1

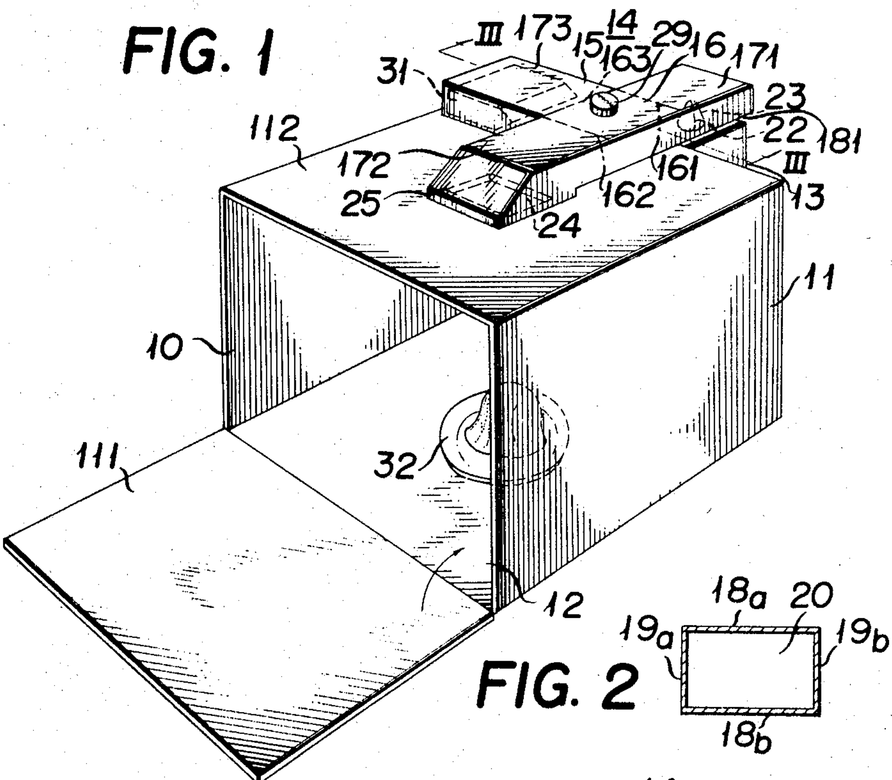


FIG. 2

FIG. 3

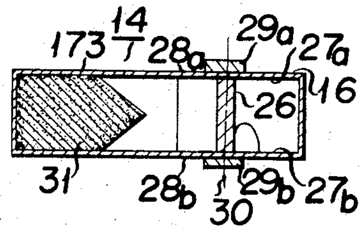
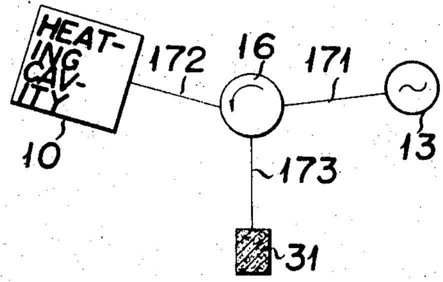


FIG. 4



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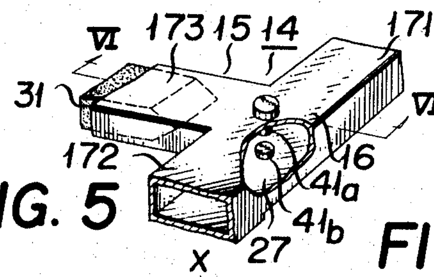


FIG. 5

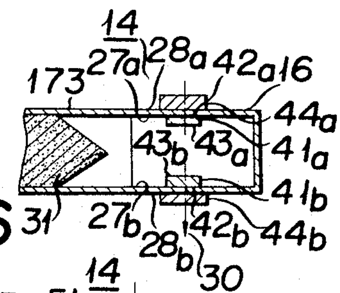


FIG. 6

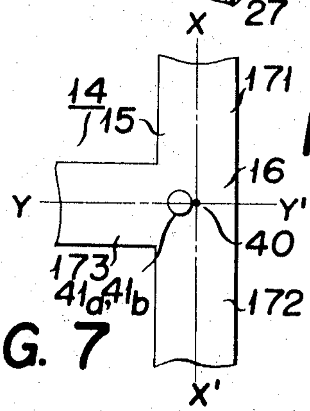


FIG. 7

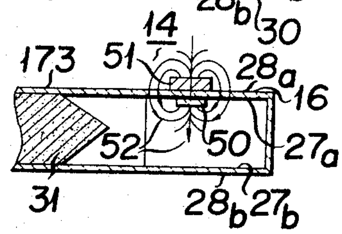
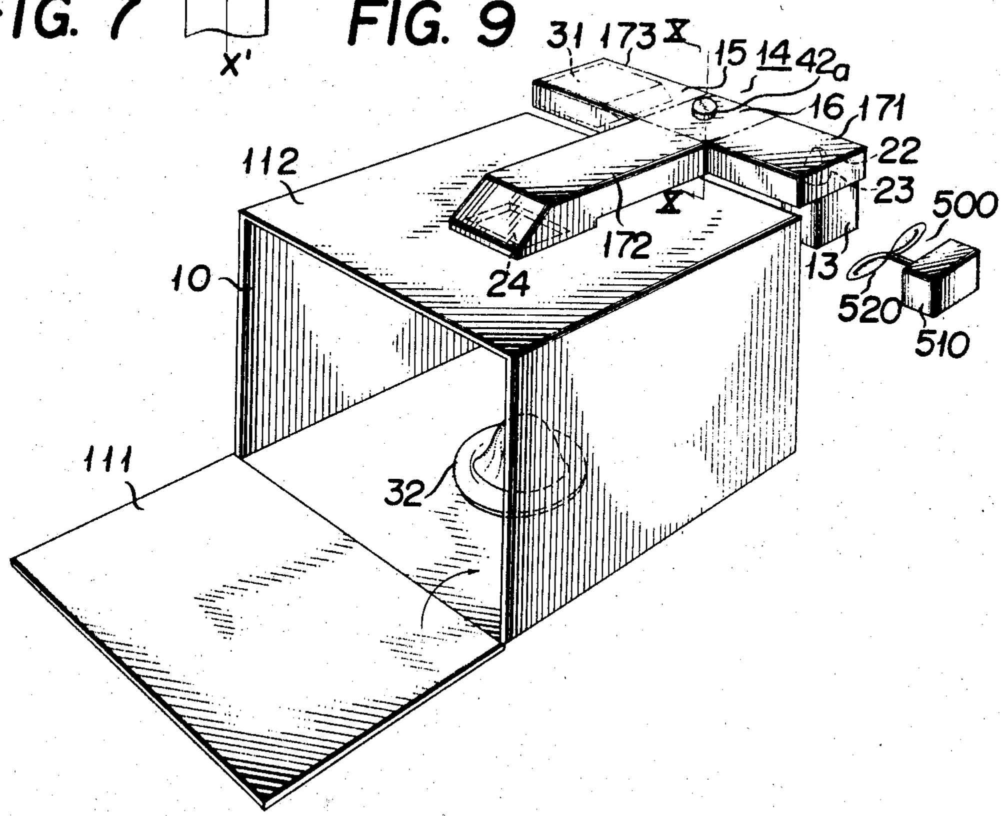


FIG. 8

FIG. 9



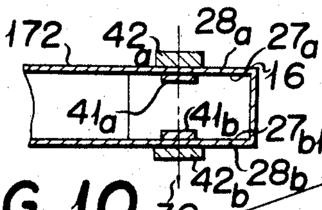
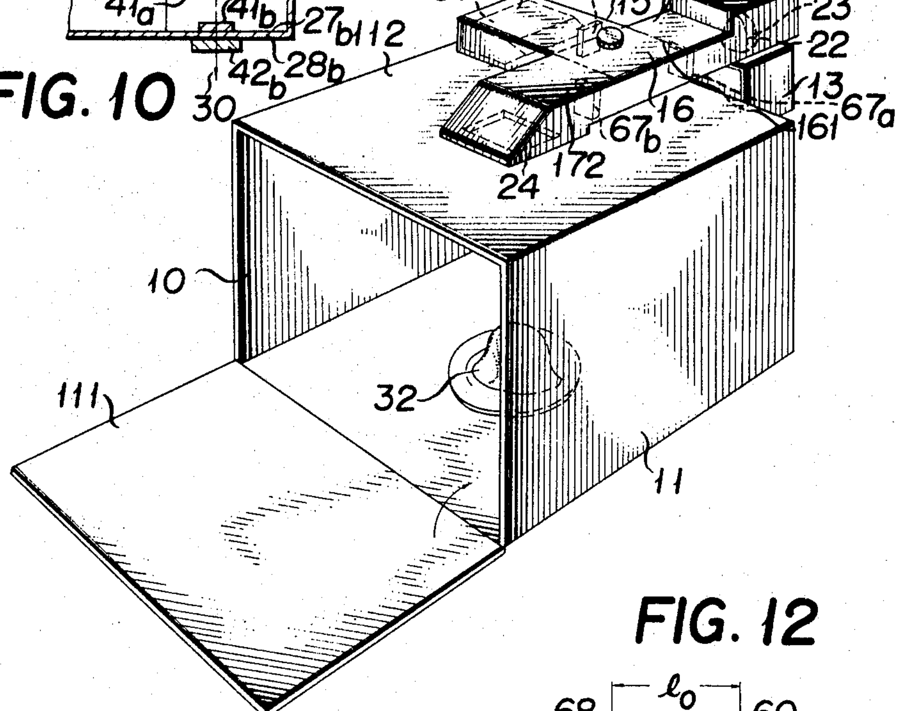
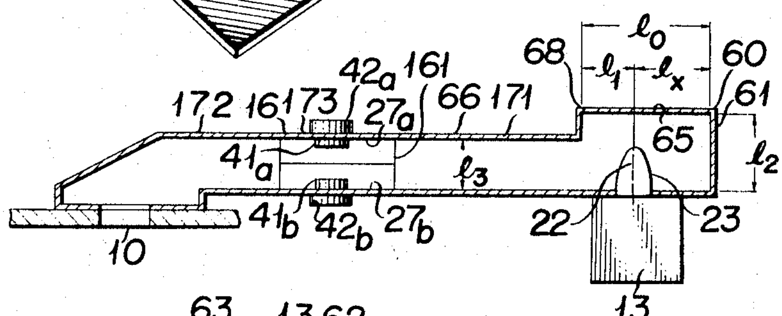


FIG. 10

FIG. 11





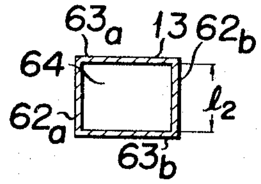


FIG. 13A

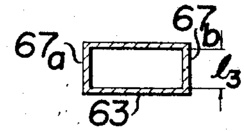
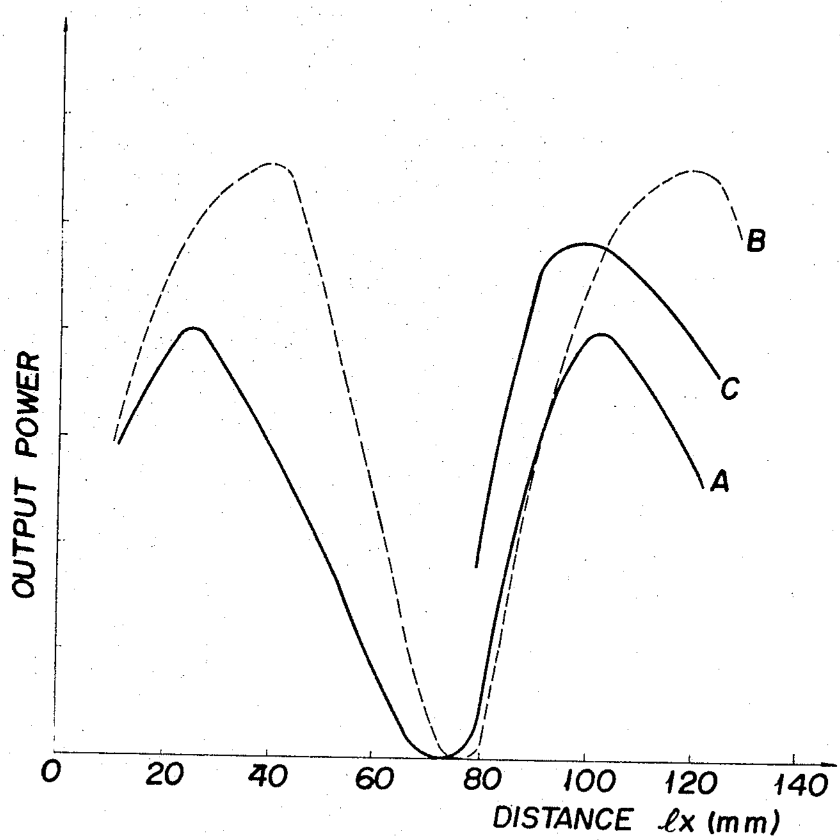


FIG. 13B

FIG. 14



3,437,777

MICROWAVE HEATING APPARATUS

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Filed June 13, 1967, Ser. No. 645,775
Claims priority, application Japan, June 17, 1966, 41/38,890; June 30, 1966, 41/42,225; Oct. 15, 1966, 41/67,423; Nov. 19, 1966, 41/75,756
Int. Cl. H05b *9/06*
U.S. Cl. 219—10.55 **13 Claims**

ABSTRACT OF THE DISCLOSURE

A waveguide connection interconnected between a microwave oscillator for supplying microwave energy and an enclosed heating cavity defined by a metal wall structure comprises at least one circulator in the form of a branched rectangular waveguide arranged to lead microwave energy reflected from the heating cavity to a microwave absorber so as to prevent the reflected microwave from returning to the microwave oscillator.

Background of the invention

This invention relates to microwave heating apparatus and more particularly to such apparatus provided with an improved arrangement for protecting the microwave oscillator included therein during no-load and light load operating conditions of the apparatus.

As is well known in the art a microwave heating apparatus is utilized to irradiate an object to be heated with microwave energy having a frequency of about 2450 mc./sec., for example, whereby to heat the object uniformly. Although such apparatus have been mainly used for heating foods or freezed foods and are called as an electronic cooking apparatus, recently applications thereof to heating, molding and working of synthetic resins and to heating and drying of pottery have become common.

Generally, a microwave heating apparatus comprises a box-like heating cavity or chamber defined by metal walls, a microwave oscillator, usually employing a magnetron, and a waveguide connection coupling the oscillator to the cavity, for supplying microwave energy generated by said microwave generator into the cavity. An object or material to be heated, for example, a foodstuff is inserted in the cavity and dielectrically heated by the irradiation of microwave. However, under light load or no-load condition wherein the object inserted in the cavity is small or there is no object, the most part of the microwave energy supplied to the cavity will be reflected to flow in the opposite direction back to said magnetron oscillator through the waveguide connection. This results in breaking down of the microwave oscillator or magnetron. In such a case, especially the cathode electrode of the magnetron often is damaged by back bombardment, thus the back bombardment not only shortens the life of expensive magnetron but also ultimately destroys it.

As an approach for preventing troubles caused by reflected waves, it has been proposed to connect a Faraday rotation type or resonance type isolator in said waveguide connector for the purpose of isolating the oscillator from the cavity and to absorb and attenuate microwave energy

reflected from the cavity as described in U.S. patents, Nos. 2,776,412, 2,929,905 and 3,210,513. However, when using a Faraday rotation type isolator, a Faraday rotator is provided in a circular waveguide to polarize electromagnetic wave by 45°, thus imparting thereto a non-reciprocal property. This arrangement required rectangular waveguides to be connected to the input, output and the third branch. The diameter of the circular waveguide required for the transmission of a microwave having a frequency of the order of 2450 mc./sec. is more than 10 centimeters. In addition, in order to connect rectangular waveguides to the both ends of a circular waveguide as well as the third branch, it is necessary to use rectangular-circular waveguide adapter, thus greatly complicating the construction of the waveguide arrangement. Moreover, it is necessary to rotate the plane of electric field by 45° by applying from an external magnetic field to a ferrite element provided in said circular waveguide.

As is well known in the art, the characteristics of ferrite element are caused to vary by temperature variation, which results in the variation of the angle of rotation of the plane of the microwave, thus deteriorating the characteristics of the isolator. This will cause attenuation of the useful microwave transmitted to the cavity. Further, as it is necessary to mount the ferrite element at the center of the waveguide there is a problem in mounting it. In microwave communication wherein the average power of the electric wave transmitted is usually less than few watts there is no serious problem. However, in microwave heating apparatus wherein the average power of microwave transmitted exceeds several hundred watts, there is a tendency that the ferrite element is overheated.

On the other hand in the apparatus utilizing a resonance type isolator using the phenomenon of ferromagnetic resonance, a thin ferrite slab is utilized. Thus, the ferrite element does not act as an isolator without being excited by an external cross-magnetic field of more than 2000 to 3000 gausses thus requiring extremely strong and bulky exciting apparatus. Further as the microwave reflected from the cavity is absorbed and attenuated by the ferrite slab, its temperature increases. By this reason it is necessary to cool the ferrite slab by means of a large cooling device.

In each of the above described prior apparatus for preventing troubles caused by reflected wave in microwave heating apparatus the construction of the isolator was complicated and bulky so that many troubles were encounted in the practical use of the microwave heating apparatus. Especially, in the heating apparatus handling average power of microwave of more than 1 kw., the isolator having a construction as above described is not only uneconomical but it also can be difficult to provide satisfactory characteristic.

Summary of the invention

One of the objects of this invention is to provide an improved microwave heating apparatus including a novel circulator between a cavity of the heating device and a microwave oscillator which is carefully designed to decrease heating effect and to prevent microwave reflected from the cavity from reaching the microwave oscillator under light load and no-load conditions effectively.

According to one embodiment of this invention there is provided a microwave heating apparatus comprising a microwave oscillator for supplying microwave energy, a metal wall structure defining a substantially closed heating cavity, and a waveguide connector between said oscillator and said cavity, said connector comprising a branched rectangular waveguide including a central waveguide section, a first rectangular waveguide branch coupled to said oscillator to receive microwave therefrom, a second rectangular waveguide branch coupled to said cavity and a third rectangular waveguide branch, said first, second and third branches extending radially in different directions from said central section, a ferrite element mounted in said central waveguide section at a circularly polarized position, means including an exciting element mounted on said central waveguide section against said ferrite element to apply thereto magnetic field whereby to introduce said microwave into said heating cavity through said central waveguide section and said first and second branches and to direct microwave reflected from said cavity into said third branch, and a microwave absorber contained in said third branch to absorb reflected microwave.

According to another embodiment of this invention there is provided a microwave heating apparatus comprising a microwave magnetron oscillator for supplying microwave energy, a metal wall structure defining a substantially closed heating cavity, one of the metal side walls defining said cavity being substantially flat and being provided with an inlet opening for admitting said microwave, and a waveguide connector between said oscillator and said heating cavity, said connector including an H plane branched T-shape waveguide comprising a central waveguide section, a first rectangular waveguide branch on said one metal side wall of the cavity, said first branch being coupled to said oscillator at one end thereof opposite to its other end joined to said central waveguide section to receive microwave from said oscillator, a second rectangular waveguide branch colinear with said first branch, being coupled to said microwave inlet opening at one end thereof opposite to its joint to said central section, and a third rectangular waveguide section perpendicular to said first branch, said first, second, and third branches being branched from said central waveguide section in the H plane parallel to said side wall in three directions to form T-shaped configuration, at least one circular disc shaped ferrite element mounted on the inner surface of opposing broad side walls of said central waveguide section at a position to cause said microwave transmitted through said central waveguide section to create a substantially circularly polarized magnetic field, said ferrite element having a flat outer surface contacting said inner surface, means including an exciting element in the form of a disc shaped permanent magnet which is mounted on the outer surface of one of said broad side walls to oppose said ferrite element to apply thereto a magnetic field across said central waveguide section whereby to transmit the microwave in the forward direction into said heating cavity through said central waveguide section and through said first and second branches and to direct microwave reflected from said heating cavity toward said third branch and an electric wave absorber provided in said third branch.

This invention will be more fully set forth in the following detailed description with reference to the accompanying drawings, and the features of novelty which characterize this invention will be pointed out with particularity in the claims annexed to and forming a part of this specification.

Brief description of the drawings

FIG. 1 is a schematic perspective view of one embodiment of the microwave heating apparatus according to this invention;

FIG. 2 shows a cross section of a rectangular waveguide utilized in the apparatus shown in FIG. 1;

FIG. 3 is a cross section view taken along a line III—III in FIG. 1;

FIG. 4 is a diagrammatic representation of the principle of the heating apparatus shown in FIG. 1;

FIG. 5 is a partial view, partly broken away, showing a circulator utilized in a modified microwave heating apparatus;

FIG. 6 is a sectional view taken along a line VI—VI in FIG. 5;

FIG. 7 is a plan view of the portion shown in FIG. 6;

FIG. 8 is a sectional view particularly illustrating the central rectangular waveguide section employed in another modification of the microwave heating apparatus embodying this invention;

FIG. 9 is a schematic perspective view of a still further modification of the microwave heating apparatus of this invention;

FIG. 10 is a sectional view taken along a line X—X in FIG. 9;

FIG. 11 is a schematic perspective view of yet another modification of the heating apparatus embodying this invention;

FIG. 12 is a longitudinal sectional view of the circulator connector employed in the microwave heating apparatus shown in FIG. 11;

FIG. 13A is a cross sectional view of the junction for coupling a magnetron oscillator;

FIG. 13B is a cross sectional view of the other junction; and

FIG. 14 is a graph to show the experimental result of the microwave heating apparatus shown in FIG. 11.

Detailed description of the invention

The microwave heating apparatus embodying this invention is characterized in that it utilizes a branched type circulator in a rectangular waveguide for eliminating troubles caused by reflected microwaves. Referring to FIG. 1 which shows a perspective view of a preferred embodiment of this invention a heating cavity or chamber **10** is a metal box comprised by flat metal wall **11**, one of which **111** being pivotally connected at its lower edge to form an opening **12** through which an object to be heated is inserted into and removed from the cavity. As shown in FIG. 4, a magnetron oscillator **13** is provided near the heating cavity **10**. The magnetron oscillator **13** is supplied with a high voltage from a source of supply, not shown, to generate microwave energy of the frequency of about 2450 mc./sec., for example. The magnetron oscillator **13** and the heating cavity **10** are interconnected by a waveguide connection **14** including a circulator of the rectangular waveguide branched type. The connection **14** including the circulator is utilized for the purpose of transmitting microwave energy from the magnetron oscillator **13** to the heating cavity **10** with small loss and at a high efficiency and to attenuate microwave energy reflected from the heating cavity **10** back to the magnetron oscillator **13**.

The construction of the connection **14** is as follows: On one side wall of the heating cavity **10**, for example, the upper wall **112**, is mounted an H plane branched T-shaped rectangular waveguide **15** of H_{10} mode. The H plane branched T-type rectangular waveguide **15** includes a first rectangular waveguide branch **171**, a second rectangular waveguide branch **172**, and a third rectangular waveguide branch **173** which are radially branched from a control waveguide section **16** having a rectangular cross section, more particularly branched in three directions at the H plane, in a letter T configuration. As shown in FIG. 2, each of the first, second and third rectangular waveguide branches **171**, **172** and **173** have broad side walls **18***a* and **18***b* each having a width of 76 mm. and narrow side walls **19***a* and **19***b* each having a width of 55.8 mm., for example. The cross section **20** of these branches is rectangular. These first, second and third waveguide branches **171**, **172** and **173** are interconnected by the central waveguide section **16**. As shown in FIG. 1, the first and second branches **171** and 172 are arranged on the same straight line, and the third branch 173 is arranged perpendicularly to the first and second branches 171 nad 172. The first branch 171 is coupled to the oscillator 13 on the side opposite to the junction 161 between the first branch and the central waveguide section 16. An antenna 22 covered by a protective cover transparent to microwave and adapted to radiate microwave from the oscillator 13 extends through the lower broad side wall 181 of the first branch 171 to project therein and coupled therewith. On the other hand, the second waveguide branch 172 is coupled to the wave inlet opening 24 of the heating cavity 10 on the side of the branched portion 162 between the second branch and the central waveguide section 16, and the second branch 172 is formed with a corner bend 25 at the portion thereof coupled to the wave inlet opening 24. One end of the third branch 173 is coupled to the central waveguide section 16 at a branched portion 163 and the opposite end is closed. As shown in FIG. 3, a circular column shaped ferrite element 26 is mounted in the central waveguide section 16, the both ends of the ferrite element 26 being in contact with the opposing inner surfaces 27*a* and 27*b* of broad side walls. The position of the ferrite element 26 is selected so as to provide satisfactory three part circulator action by the described branched waveguide structure.

Exciting elements 29*a* and 29*b* are mounted to face the both ends of the ferrite element 26 on the broad outer side walls 28*a* and 28*b* of the central waveguide section 16 to provide for the ferrite element a cross-magnetic field of the intensity of about 300 to 600 gausses in the direction shown by arrow 30 perpendicular to the waveguide section 16. When excited by this cross-magnetic field the ferrite element 26 permits transmission of the microwave supplied by the oscillator 13. The exciting elements 29*a* and 29*b* may be electromagnets or permanent magnets so long as they can provide aforementioned cross-magnetic field. In the illustrated embodiment a pair of disc shaped permanent magnets of barium-ferrite are utilized.

When the waveguide section 16, ferrite element 26 and exciting elements 29*a* and 29*b* are arranged in the relation mentioned above the connection 14 acts as a circulator as is well understood by those skilled in the art. Microwave energy introduced into the first branch 171 from the magnetron oscillator 13 is transmitted through the central waveguide section 16 and appears the second branch 172, energy reflected from the cavity appears to the third branch 173 and energy input to the third branch by some reasons put out to the first branch 171. FIG. 4 shows the principle of the operation of the circulator.

A block shaped electromagnetic wave absorber 31 is disposed in the third rectangular waveguide branch 173. The wave absorber 31 is made of a sintered body of clay of comb structure and Carborundum. One end of the microwave absorber 31 is tapered to perfectly absorb microwave without any reflection. Then during forward transmission, the microwave from the oscillator 13 is transmitted into the cavity 10 with little loss through the first and second branches 171 and 172, and the wicrowave reflected from the cavity 10 is transmitted back to the second branch 172, and is then absorbed and attenuated by the electromagnetic wave absorber 31 contained in the third branch 173. In other words, although the microwave generated by the oscillator 13 is transmitted to cavity 10 with little loss, the microwave reflected from the cavity 10 is absorbed by the absorber 31 and can not flow back the magnetron so that the connection 14 as a whole of the circulator construction operates as if it were an isolator.

The isolating characteristic of the connection 14 exhibiting the characteristic of a circulator at a microwave frequency of 2450±50 mc./sec. was measured over the range of temperature 0 to 100° C. The insertion loss in

the transmission direction of microwave energy from oscillator 13 to cavity 10 was about 0.1–0.2 db whereas attenuation quantity in the opposite direction, that is the attenuation quantity of the reflected wave was more than 25 db.

The operation of the microwave heating apparatus constructed as above described is as follows: After inserting an object to be heated 32 which is supported by a vessel in the heating cavity 10, the front door 111 is closed. Then a prescribed operating power is supplied to the magnetron oscillator 13 to initiate its oscillation thereby to radiate microwave of an average power of 500 w. from the antenna 22. This microwave travels straightly with little loss and without any appreciable attenuation through the first and second branches 171 and 172 to be introduced in the cavity 10.

When the user accidentally closes the door 111 without inserting the object, or the volume thereof is small, no-load or light load condition will be resulted, thus creating an undesirable standing wave.

As a result, a portion of the microwave energy supplied will be returned to the connection 14 as the reflected wave. However, as has been pointed above, since a three-branched circulator is formed by the ferrite element 26 contained in the central waveguide section 16 almost all portion of the reflected microwave energy will be directed to the third branch 13 and attenuated by the electric wave absorber 31 contained therein. In this manner, arrival of the reflected microwave energy at the magnetron oscillator 13 can be positively prevented.

By the use of a circulator of the waveguide branch type, the microwave heating apparatus of this invention is advantageous over prior apparatus in the following points.

Firstly, the branched rectangular waveguide 15 comprising the main body of the circulator structure is simple in construction, thus enabling to construct it small size. In addition, the ferrite element 26 is thin and is mounted in contact with the opposing broad side walls of the central waveguide section 16, heat generated therein by the microwave will be transmitted to these side walls and immediately dissipated. Thus, there is no fear of overheating the ferrite element 26 so that it can always function as desired. In addition since the intensity of the magnetic field applied to the ferrite element is about several hundred gausses, the exciting elements 27 may be of small size. For instance, they may be disc shaped permanent magnets having a diameter of 50 to 60 mm. and a thickness of 15 mm. Thus, as the construction of the connection 14 is simple and small size it can be manufactured at low cost. In addition to this advantageous construction, it is very effective to prevent troubles caused by reflected microwaves because of its high transmission loss in the reverse direction of more than 25 db.

Referring again to FIG. 1, as the H plane T-branch waveguide 15 is arranged with its H plane in parallel with the side wall 112, the overall height of the heating cavity 10 and the waveguide structure can be reduced. Ideally, in order to reduce the height it is advantageously to intimately contact the H plane T-branch waveguide 15 against the upper wall 112. If the second and third branches 172 and 173 intersecting at right angles are mounted on the upper wall 112, the space required can be saved and the width of the structure can be reduced. As the upper wall 112 is a rectangle having length and width of several ten centimeters, it is very easy to mount the central waveguide section 16 and the second and third branches 172 and 173 on the upper wall 112. From the standpoints of fabrication and adjustment, it is preferable to arrange the waveguide branches 172 and 173 in parallel with the side wall 11. If the end of the first waveguide branch 171 opposite to the joint 161 were projected slightly away from wall 112, the magnetron oscillator 13 could be conveniently connected to the lower surface of the projected portion of the first branch 171. As the microwave energy is radiated, the magnetron oscillator **13** will be heated considerably, the above described arrangement permits the cooling of the magnetron alone by the independent cooler, not shown, whereby to stabilize its oscillation.

In the embodiment shown in FIG. 1 a circular column shaped ferrite element **26** is mounted to contact with the opposing inner surfaces of broad side walls of the central waveguide section **16**. In this case the height of the ferrite element **26** was made to be equal to the width of narrow side walls, or about 55.3 mm. Though a heat loss is generated in the ferrite element **26** as the microwave is transmitted at the element **26**, the construction shown in FIG. 1 is satisfactory when the energy of the microwave oscillated from the microwave oscillator **13** is at the order of several hundred watts. However, when the average output of the microwave oscillator **13** increases to more than 1 kw., the temperature of the ferrite member **26** mounted between upper and lower side walls will be increased due to heat generated therein. Thus, during transmission of large microwave energy the temperature of the ferrite element may exceed the Curie point, which is of course undesirable.

The following embodiment shows a modification of the microwave heating apparatus of this invention wherein the ferrite element can maintain its suitable temperature, thus providing adequate isolation effect even when handling average output of the microwave energy of more than 1 kw. This modification will be described by referring to FIGS. 5 to 7 in which only the connector **14** comprising the circulator and adapted to interconnect them is shown, since the construction and arrangement of the cavity and magnetron oscillator are the same as those shown in FIG. 1.

The H plane T-branch rectangular waveguide **15** of the H_{10} mode is identical to that shown in FIG. 1. Again, the waveguide **15** includes a first rectangular waveguide branch **171**, a second rectangular waveguide branch **172** and a third rectangular waveguide branch **173** which are arranged in a letter T configuration and radially branched at the H plane. Two ferrite elements **41***a* and **41***b* are disposed in the central waveguide section **16** at a point slightly displaced from the point of branching **40** or a point of intersection of the X–X′ axis and the Y–Y′ axis which divide equally in broad side of the branch **171**, **172** and in that of **173**, respectively. More specifically, on the inner walls of broad side walls **27***a* and **27***b* of the waveguide section **16** are mounted a pair of thin disc-shaped ferrite elements **41***a* and **41***b* at said point. The ferrite elements comprise disc having a diameter of 45 mm. and a thickness of 5 mm., for example, with flat surfaces **42***a* and **42***b* and **43***a* and **43***b*, for the surfaces **42***a* and **42***b* contacting with said inner walls **27***a* and **27***b*. On the opposite surfaces **28***a* and **28***b* of the broad side walls are secured a pair of exciting elements **44***a* and **44***b* in the form of disc-shaped permanent magnets which supply cross-field in the direction of an arrow **30** shown in FIG. 6 to ferrite elements **41***a* and **41***b*. Thus, the connection **14** acts as a circulator.

Accordingly, the microwave injected into the first branch **171** coupled to the magnetron oscillator will be transmitted with low loss toward the second branch **172**, the opposite end thereof being coupled to the heating cavity. The reflected microwave energy injected into the second branch **172** from the heating cavity is transmitted at low loss into the third branch **173** which contains an electric wave absorber **31**. Thus the connection **14** operates as if it were an isolator. The following good results were obtained when an object in the heating cavity was heated by the microwave energy supplied by the magnetron oscillator.

While a pair of thin disc shaped ferrite elements **41***a* and **41***b* were substituted for an elongated ferrite element **26** shown in FIG. 3, when transmitting a microwave energy of 2450 mc./sec., the insertion loss of ferrite in the direction of transmission was about 0.2 db, the transmission loss in the opposite direction was more than 25 db. It is to be particularly noted that when microwave of said frequency was transmitted at an average power of 3 kw., the temperature rise of ferrite elements **41***a* and **41***b* was only 25° C. above room temperature. Thus, even with such a large power, it was possible to maintain the temperature of the ferrite elements **41***a* and **41***b* at an adequate value without utilizing any cooling device. In addition, the isolation of more than 25 db was satisfactory to protect the magnetron oscillator from the reflected wave. These satisfactory results are very desirable to high capacity microwave heating apparatus handling large microwave energy of more than several hundred watts.

Reasons for such good results lie in flat surface of the ferrite elements, correspondingly in tight contact between the ferrite elements and the side walls **27***a* and **27***b*, and lie in extremely thin thickness. These factors contribute to greatly decrease in the ferrite insertion loss in the direction of transmission as well as the heating of the ferrite elements caused by the transmission loss of the reflected wave from the cavity side. Ferrite elements utilized in the modification shown in FIG. 5 can be manufactured very readily and economically by mass-production scale because they are in the form of flat discs. While the configuration of the ferrite elements may be triangular, square or any other shape, circular configuration is preferable because of its easy fabrication and easiness of determining its center, thus fabricating its positioning on said branching point **40**. Thus, although the configuration of the ferrite elements is not critical it is preferable to make their thickness thin and to make their opposite surfaces flat and have substantially the same configuration. Further it should be understood that thickness of the ferrite elements is not limited to aforementioned value but it was confirmed by experiment that elements having a thickness thinner than their maximum width can provide the same merits as said example. For example, in circular disc shaped elements having a diameter of 45 mm., thin thickness is selected to be less than 22.5 mm. However they must have a certain thickness because they are required to provide a phase difference of about 90° between left-hand and right-hand polarized waves in the waveguide when microwave is transmitted through ferrite elements. According to experiment, a thickness less than about 2 mm. seemed appropriate.

While in the above description regarding the embodiment shown in FIGS. 5 to 7, a pair of disc shaped ferrite elements are mounted on the opposing inner walls of broad side walls in order to provide a connector of the circulator construction one of the ferrite elements may be omitted as shown in FIG. 8. In FIG. 8, branched rectangular waveguide has not been shown because it is identical to that employed in the above-mentioned embodiments. Thus, as shown in FIG. 8 only one disc shaped ferrite element **50** is mounted in the central section **16** of the H plane T-branch rectangular waveguide, at a position slightly displaced from the center toward the third branch **173**, as in FIG. 7, said position being a circularly polarized position at which the microwave transmitted through the central section **16** of the waveguide creates a circular polarized magnetic field. An exciting element in the form of a disc shaped permanent magnet **51** is mounted on the outer wall **28***a* to oppose the ferrite element **50** whereby to supply a magnetic field distributed as shown by arrows **52** to the ferrite element to cause it to operate as a circulator. However, as an electromagnetic wave absorber **31** is contained in the third branch **173**, the connection itself of the circulator construction operates as an isolator to attentuate the microwave reflected from the heating cavity.

Ferrite element **50** mounted on the inner wall **27***a* is a circular disc having a diameter of 50 mm. and a thickness of 5 mm. for example, and the exciting element **51** is a disc shaped barium ferrite permanent magnet having a diameter of 55 mm. and a thickness of 10 mm. With such a thin ferrite element **50** with contact to the inner wall **27***a* of the broad side wall, when microwave of a frequency of 2450 mc./sec. transmitted, the insertion loss of the ferrite in the direction of transmission was only 0.2 db while the transmission loss in the opposite direction was more than 25 db. When microwave energy of the mean power of 1 kw. was supplied the temperature rise above room temperature of ferrite element **50** was only 5° C. Thus, so long as the thickness of the ferrite element is sufficiently thin, use of only one ferrite element **50** and only one exciting element **51** is sufficient for practical use. In fact it was able to eliminate troubles caused by the reflected wave, under light load or no-load condition. Even when the diameter of the ferrite magnet or the exciting element **51** was selected smaller than that of the ferrite element **50**, electrical characteristics, viz the ferrite insertion loss in the direction wave transmission and the transmission loss in the opposite direction did not deteriorate.

In the heating apparatus shown in FIGS. 5 to 7, since a pair of ferrite elements are mounted on the opposed inner walls of the waveguide, it is necessary to shape them symmetrically to face each other and to mount them symmetrically to face each other. However, in the modification shown in FIG. 8, as only one ferrite is utilized such symmetrical shaping and arrangement are unnecessary. Moreover, this arrangement is more economical because the cost of material of the ferrite element and of the exciting element is reduced to one half. However, in the arrangement shown in FIG. 8, the ferrite element will be subjected to twice heating effect of the configuration of the ferrite element were the same as that utilized in FIGS. 5 to 7. As a consequence, in the arrangement shown in FIG. 8 it is desirable to make thin as far as possible the thickness of the ferrite element. As a result of experiment it was confirmed that the heating effect could be ignored if the thickness of the single ferrite element utilized in the modification shown in FIG. 8 were less than one half of the maximum width. For example, in a disc shaped ferrite element having a diameter of 50 mm., the thickness may be less than 25 mm.

FIG. 9 shows a still further modification of this invention wherein the H plane branched T-shaped rectangular waveguide comprising the connector, the heating cavity and the magnetron oscillator are arranged in a different manner. An H plane T-branch rectangular waveguide **15** is mounted on the upper wall **112** of a heating cavity **10**. Again a first, a second, and a third rectangular waveguide branches **171, 172** and **173** are branched from a central waveguide section **16** to form a letter T configuration. However, this modification is different from previous embodiments in that the first and the third rectangular waveguide branches **171** and **173** are disposed on the same straight line and that the second rectangular waveguide branch **172** is arranged to intersect said straight line at right angles. An antenna **22** which radiates microwave energy is projected into the first branch **171** to couple it with a magnetron oscillator **13**. The second branch **172** is coupled with the heating cavity **10** through a microwave inlet opening **24**. Within the third branch **173** with its outer end closed is positioned an electric wave absorbing block **31** having a tapered end. Like the arrangement shown in FIG. 6, a pair of circular disc-shaped ferrite element **41***a* and **41***b* are mounted on the opposing broad side walls **27***a* and **27***b* of the central waveguide section **16**, and a pair of exciting elements **42***a* and **42***b* are mounted on the outer surface **28***a* and **28***b* to oppose ferrite elements **41***a* and **41***b*, respectively, whereby to supply a magnetic field to the ferrite elements in the direction shown by the arrow **30** in FIG. 10. With this construction, the microwave energy supplied to the second branch **172** will be bent and transmitted to the heating cavity **10**. Whereas the microwave energy reflected from the heating cavity **10** will be bent and directed into the third branch **173** to be absorbed and attenuated by the microwave absorber **31**. In this embodiment too, the connection **14** intercoupling the magnetron oscillator **13** and the heating cavity **10** is constructed to operate as a circulator, thus operating stably as an isolator to attenuate the reflected microwave. Losses of the connection in the forward and reverse directions were substantially the same as those of afore-described embodiments. It is of course necessary to cool the magnetron oscillator by means of a suitable cooling device to remove heat generated therein during operation. Utilization of a cooling fan **500** results in the following advantages. Fan blades **520** driven by an electric motor **510** induce a flow of forced cooling air along said first and third branches arranged on a straight line. In order to eliminate to the maximum extent troubles caused by the reflected wave, or to attain the object of this invention, it is necessary to prevent the temperature rise of the microwave absorbing body **31** caused by the absorbed microwave. The cooling fan **500** firstly cools the magnetron oscillator which is liable to suffer overheating, then cools the central waveguide section **16** to prevent undesirable temperature rise of ferrite elements **41***a* and **41***b* and finally cools the third rectangular waveguide branch **173** to cool the microwave absorbing body **31** contained therein. By constant cooling of the absorbing body **31** it is able to prevent positively troubles caused by reflected waves even when the apparatus is used inadvertently over a long time. Collinear arrangement of the magnetron oscillator **13** requiring cooling and the third branch **173** housing the electromagnetic wave absorbing body **31** enables effective cooling by means of a common cooling fan.

As shown in FIGS. 1 to 9, there have been shown two types of H plane T-branch type rectangular waveguide comprising connections of the circulator construction and adapted to couple magnetron oscillators to heating cavity. However, another arrangement of the H plane T-branch type rectangular waveguide comprising the circulator structure may be used wherein the second and the third rectangular waveguide branches are arranged to intersect with the first section at right angles. Of course said second and third branches are arranged collinearly. In this modified arrangement the first branch is coupled with a magnetron oscillator, the second branch to a heating cavity and the outer end of the third branch is closed to contain a microwave absorbing body.

Thus there are provided three different arrangements for the magnetron oscillator, heating cavity and microwave absorbing body by various arrangements of the H plane T-branch type rectangular waveguides disclosed in the foregoing modifications. Any desired one of the arrangements may be used dependent upon the field of application. The possibility of such three different arrangements can be well understood from FIG. 4 which shows the principle of the novel connection of the circulator construction. More particularly, if the first, second and third waveguide branches branched from the central waveguide section in three different directions were arranged in the forward direction in the order mentioned, the relative position among respective branches would be independent of the condition required to comprise the circulator structure. Thus, although in the above embodiments the circulator structures were comprised by H plane T-branch type rectangular waveguides, the circulator structure can also be provided by an H plane branched Y shaped rectangular waveguide wherein respective waveguide branches are branched from the central waveguide section at the H plane in the form of a letter Y.

Further more than three rectangular waveguides may be branched in different directions from the central waveguide section whereby to connect the first branch to the magnetron oscillator, the second branch to the heating cavity and to insert the electric wave absorbing body in the third branch. Remaining branches may be used for other purposes. Alternatively, instead of an H plane branched rectangular waveguide, an E plane branched rectangular waveguide can also be used wherein more than three rectangular waveguide branches are branched in different directions at E plane. However, for microwave heating apparatus produced in mass-production scale, it is advantageous to construct the circulator by utilizing the H plane branched T-shaped rectangular waveguides because the latter waveguides are easy to fabricate and can be readily coupled to heating cavity and magnetron oscillator.

As has been discussed hereinabove, troubles caused by reflected wave can be positively eliminated by intercoupling the heating cavity and the magnetron oscillators by utilizing the novel connection of the circulator construction which is simple in construction, easy to fabricate and suitable for large power microwave. The ferrite element and the exciting element utilized for applying magnetic field to the ferrite element, the essential elements of the connection comprising the circulator, are relatively expensive, especially when the exciting element has the form of a permanent magnet of barium ferrite in which case both elements are made of a material of ferrite series which is relatively inexpensive.

A further modification of this invention shown in FIGS. 11 through 14 relates to an improved construction of connection of the circulator cnostruction wherein the quantity of ferrite material is reduced as far as possible. As shown in FIG. 11, the connection **14** of the circulator construction and adapted to interconnect the heating cavity **10** and the magnetron oscillator **13** comprises an H plane branch T-shaped rectangular waveguide identical to those illustrated in the foregoing embodiments. A pair of disc shaped ferrite elements **41***a* and **41***b* are secured to opposing broad side walls **27***a* and **27***b* of the central waveguide section **16** and a pair of exciting elements comprising disc shaped permanent magnets are mounted on the outside of these side walls to oppose ferrite elements. The outer end **60** of the first rectangular waveguide branch **171** opposite to the branched portion **161** to the central section **16** is closed by a short circuiting end wall **61**. As shown in FIG. 13A, the region between this end and a point spaced therefrom by l_0 for example 160 mm., constitutes a branch for coupling to the magnetron oscillator, which is defined by narrow side walls **62***a* and **62***b*, each having a width of 55.3 mm. and broad side walls **63***a* and **63***b* each having a width of 96 mm. Between the branch **65** for coupling to the magnetron and the branched portion **161** is provided a branch section **66** which includes broad side walls of a width of 96 mm. which is the same as the width of said broad side walls **63***a* and **63***b*. However the width of the narrow side walls **67***a* and **67***b* is smaller than that of the narrow side walls **62***a* and **62***b* of the branch **65** and has a value of 27 mm. Thus, the first rectangular waveguide branch **171** is comprised by the branch **65** for coupling to the magnetron and said branch section **66**, the joint between them being stepped. An antenna **22** of the oscillator **13** extends into be branch section **65** perpendicularly through an opening provided through the bottom wall of the branch section. The second branch **172** is disposed collinearly with the first branch **171** and has the same cross sectional area as the first branch. The opposite end of the second branch is coupled to the heating cavity **10** via wave inlet opening **24**.

The third branch **173** is disposed at right angles with respect to first and second branches **171** and **172** and is designed to have the same cross sectional area as that of the branch section **66**. A microwave absorbing body **31** is contained in the closed end of the third branch **173**.

As the H plane branch T-shaped waveguide **15** comprises the first, second and third branches **171**, **172** and **173** of the dimension and relative position mentioned above, the width l_3 of the narrow side wall of the central waveguide section **16** if 27 mm. In other words, the spacing between broad side walls **27***a* and **27***b* of the central waveguide section is equal to 27 mm. As can be clearly noted from FIG. 12, the branch section **65** projects above the upper surfaces of other waveguide portions including the central waveguide section **16** which have the same height. Since the commonly used standard width of the broad side wall of conventional rectangular waveguides for transmitting microwave energy of 2450 mc./sec. is 96 mm. and that of the narrow side wall is 55.3 mm., only the branch section of the H plane branched T-shaped rectangular waveguide **15** adapted to couple to the magnetron oscillator is required to have the same dimension as the standard dimension and dimensions of other portions of the rectangular waveguide, especially of the narrow side walls have been reduced to about one half of the standard dimension. Decrease in the width of the narrow walls results in the following advantages. More particularly, as the spacing between opposing exciting elements **42***a* and **42***b* decrease, magnetic field applied to the ferrite elements can be increased. Stated in another way, the physical size of the exciting elements **42***a* and **42***b* can be reduced correspondingly, thus enabling to save ferrite permanent magnets. Further it is able to reduce the volume of the ferrite elements **41***a* and **41***b*. For example they can be shaped into discs, 40 mm.-diameter and about 5 mm.-thick, for example, thus greatly decreasing the materials for exciting elements and ferrite elements.

Where a connection of the circulator construction having especially small narrow side walls is utilized to couple the magnetron oscillator to the heating cavity, the heating cavity containing the object to be heated, as viewed from the magnetron oscillator side, always satifies the condition of matched load. Provision of irises **67***a* and **67***b* at positions illustrated by dotted lines in FIG. 11 further improves matching. As the first rectangular waveguide section **171** is joined in a step like fashion with the branch section **65** adapted to couple to the magnetron oscillator and the branch section **66** having different width of narrow side walls, according to the conventional arrangement it would be impossible to transmit at high transmission efficiencies microwave energy from the magnetron oscillator to the central waveguide section **16** unless providing a stepped matching means which is $\frac{1}{4}\lambda$ in lengths (λ represents the wavelength in the waveguide of the microwave having a frequency of 2450 mc./sec.). However, such a matching means of $\frac{1}{4}\lambda$ in lengths is not necessary because the spacing between the antenna **22** of the magnetron oscillator and the short circuiting end wall **61** is determined by the conditions to be described later.

According to various experiments made by the applicants, best matching condition does not always results maximum output, but instead, it was found that in order to obtain maximum output it is necessary to add a reactance of a certain value. The value of this reactance can be adjusted by varying the spacing l_x between the short circuiting end wall **61** behind the antenna and the antenna **22**. FIG. 14 shows measured values of the microwave energy in the heating cavity **10** supplied from the magnetron oscillator by variously changing said spacing l_x by moving the short circuiting end wall **61** while maintaining the spacing l_1 between the antenna **22** and the stepped end **68** of the branch section **65** at a constant value, 40 mm. for example. The abscissa of FIG. 14 represents the spacing between the antenna **22** and the short circuiting end wall **61** while the ordinate the relative output power of the magnetron oscillator measured in the heating cavity **10**. Where a magnetron 2M66 having the mean output of 800 w. is utilized in the magnetron oscillator **13**, the maximum output was obtained when the short circuiting end wall **61** was positioned at distances of 25 mm. and 102 mm. from the antenna as shown by a curve A. Whereas when a magnetron 2M89 having the mean output of 1.4 kw. is utilized, the maximum output could be obtained when the short circuiting end wall **61** was positioned at distances of 40 mm. and 120 mm. from the antenna as shown by a curve B. Further when a magnetron M4514B having the mean output of 2.5 kw. is used the maximum output was obtained when the short circuiting end wall 61 was positioned at a distance of 97 mm. from the antenna 22, as shown by a curve C.

Thus, it can be noted from FIG. 14 that maximum output can be obtained when the distance between the antenna 22 and the short circuiting end wall 61 is selected in ranges of 11 mm. to 54 mm. and 86 mm. to 128 mm. respectively. Accordingly even though the height of the central waveguide section containing the ferrite element is smaller than that of the branch section adapted to couple to the magnetron oscillator the maximum microwave energy will be supplied to the heating cavity by selecting the distance between an antenna and the short circuiting end wall of said branch section. It was found that the connection acting as circulator as shown in FIG. 11 operated as a satisfactory isolator to prevent troubles ensued by the reflected waves, and that the insertion loss in the direction of transmission was less than 0.2 db and the attenuation in the opposite direction was more than 25 db.

As is obvious from the foregoing descriptions regarding various embodiments of this invention, the microwave heating apparatus of this invention is especially suitable to operate as a so-called electronic range because it utilizes a simple connector of the circulator construction which can positively prevent troubles caused by reflected microwave. Further in spite of addition of such a preventing means, the physical dimension of the connection does not become bulky. The novel microwave heating apparatus can also be used for dielectric heating and working of various materials and articles.

While various embodiments of the invention have been described in the foregoing specification and illustrated in the accompanying drawings, the invention is not to be considered as limited thereto. The scope of the invention is defined solely in the appended claims.

What is claimed is:

1. A microwave heating apparatus comprising a microwave oscillator for supplying microwave energy; a metal wall structure defining a substantially closed heating cavity; and a rectangular waveguide connection between said oscillator and said cavity, said connection including:

at least first, second and third branched rectangular waveguides interconnected by a central waveguide section having a rectangular cross section, a first rectangular waveguide branch being coupled to said oscillator to receive microwave energy therefrom, and a second rectangular waveguide branch being coupled to said cavity, said first, second and third branches extending radially in different directions from said central section;

at least one ferrite element mounted on the inner side walls of said central waveguide section at a circularly polarized position, said ferrite element being in the form of a plate having a flat surface in contact with said inner side walls;

means including an exciting element mounted on said central waveguide section adjacent said ferrite element to apply thereto a magnetic field such that said microwave energy is introduced into said heating cavity through said central waveguide section and said first and second branches, and to direct microwave energy reflected from said cavity into said third branch; and

an electromagnetic wave absorber contained in said third branch to absorb said reflected energy.

2. The microwave heating apparatus according to claim 1 wherein said connection comprises:

at least first, second and third H plane branched rectangular waveguides interconnected by a central waveguide section having a rectangular cross section, a first rectangular waveguide branch being coupled to said oscillator to receive microwave energy therefrom, and a second rectangular waveguide branch being coupled to said cavity, said first, second and third branches being radially branched from said central waveguide section at the H plane;

at least one ferrite element which may be secured on at least one of the opposing broad side walls of said central waveguide section at a circularly polarized position, said ferrite element being in the form of a plate having a flat surface contacting said side wall;

means including an exciting element mounted on the outer side of said at least one broad side wall of said waveguide section adjacent said ferrite element to apply magnetic field to said ferrite element to transmit said microwave energy to said heating cavity through said central waveguide section and said first and second branches, and to direct microwave energy reflected from said heating cavity into said third branch; and

a microwave energy absorber contained in said third branch.

3. The microwave heating apparatus according to claim 2 wherein said exciting element is a permanent magnet.

4. The microwave heating apparatus according to claim 1 wherein said connection comprises:

at least first, second and third H plane branched rectangular waveguides interconnected by a central waveguide section, having a rectangular cross section a first rectangular waveguide branch being coupled to said oscillator to receive microwave therefrom, and a second rectangular waveguide branch being coupled to said heating cavity, said first, second and third waveguide branches being radially branched from said central waveguide section at the H plane;

a pair of ferrite elements secured to the opposing inner surfaces of the broad side walls of said central waveguide section at a circularly polarized position, said ferrite elements being in the form of plates having flat surfaces contacting said inner surface;

means including a pair of permanent magnets mounted on the outer surfaces of said broad side walls to oppose said ferrite elements to apply a magnetic field across said central waveguide section to transmit the microwave energy in the forward direction into said heating cavity through said central waveguide section and through said first and second branches, and to direct microwave energy reflected from said heating cavity toward said third branch; and

a microwave absorber provided in a said third branch to absorb said reflected wave.

5. The microwave heating apparatus according to claim 1 wherein said connection comprises:

at least first, second and third H plane branched rectangular waveguides interconnected by a central waveguide section having a rectangular cross section, said first rectangular waveguide branch being coupled to said oscillator to receive microwave energy therefrom, and said second rectangular waveguide branch being coupled to said heating cavity, said first, second and third waveguide branches being radially branched from said central waveguide section at the H plane;

at least one circular disc shaped ferrite element mounted on the inner surface of at least one of the opposing broad side walls of said central waveguide section at a circularly polarized position, said ferrite element means having flat surface contacting said inner surface;

means including an exciting element in the form of a disc shaped permanent magnet mounted on the outer surface of one of said broad side walls to oppose said ferrite element to apply thereto a magnetic field across said central waveguide section to transmit the microwave energy in the forward direction into said heating cavity through said central waveguide section and through said first and second branches, and to direct microwave reflected from said heating cavity toward said third branch; and

a microwave absorber provided in said third branch.

6. The microwave heating apparatus according to claim 1 wherein said connection comprises an H plane branched T-shaped rectangular waveguide interconnected by a central waveguide section having a rectangular cross section, a first rectangular waveguide branch being coupled to said oscillator to receive microwave therefrom, a second rectangular waveguide branch being coupled to said heating cavity and a third rectangular waveguide branch, said first, second and third waveguide branches being branched from said central waveguide section at the H plane in three directions to form a letter T configuration a pair of circular disc shaped ferrite elements mounted on the inner surfaces of opposing broad side walls of said central waveguide section at a circularly polarized position, said ferrite elements having flat surfaces contacting said inner surfaces, means including exciting means in the form of a pair of disc shaped permanent magnets which are mounted on the outer surfaces of said broad side walls to respectively oppose said ferrite elements to apply thereto a magnetic field across said central waveguide section whereby to transmit the microwave in the forward direction into said heating cavity through said central waveguide section and through said first and second branches and to direct microwave reflected from said heating cavity toward said third branch, and a microwave absorber provided in said third branch.

7. The microwave heating apparatus according to claim 5 wherein said branched rectangular waveguide comprises an H plane branched T-shaped rectangular waveguide interconnected by a central waveguide section having rectangular cross section, a first, a second and a third branches being branched from said central section at the H plane in three directions to form a letter T configuration.

8. A microwave heating apparatus comprising a microwave magnetron oscillator for supplying microwave energy, a metal wall structure defining a substantially closed heating cavity, one of the metal side walls defining said cavity being substantially flat and being provided with an inlet opening for admitting said microwave, and a waveguide connection between said oscillator and said heating cavity, said connection including an H plane branched T-shape waveguide interconnected by a central waveguide section having a rectangular cross section, a first rectangular waveguide branch on said one metal side wall of cavity, said first branch being coupled to said oscillator at one end thereof opposite to its other end joined to said central waveguide section to receive microwave from said oscillator, a second rectangular waveguide branch collinear with said first branch, said second branch being coupled to said microwave inlet opening at one end thereof opposite to its joint to said central section, and a third rectangular waveguide section perpendicular to said first branch, said first, second and third branches being branched from said central waveguide section at the H plane parallel to said side wall in three directions to form T-shaped configuration, at least one circular disc shaped ferrite element mounted on the inner surface of opposing broad side walls of said central waveguide section at a circularly polarized position, said ferrite element having a flat outer surface contacting said inner surface, means including an exciting element in the form of a disc shaped permanent magnet which is mounted on the outer surface of one of said broad side walls to oppose said ferrite element to apply thereto a magnetic field across said central waveguide section whereby to transmit the microwave in the forward direction into said heating cavity through said central waveguide section and through said first and second branches and to direct microwave reflected from said heating cavity toward said third branch and a microwave absorber provided in said third branch.

9. A microwave heating apparatus comprising a microwave magnetron oscillator for supplying microwave energy, a metal wall structure defining a substantially closed heating cavity, one of the metal side walls defining said cavity being flat and provided with an inlet opening for admitting microwave, and a microwave connection between said oscillator and said heating cavity, said connection including an H plane branched T-shaped rectangular waveguide interconnected by a central waveguide section having a rectangular cross section, a first rectangular waveguide branch on said one metal side wall, said first branch being coupled to said oscillator at one end thereof opposite to its other end joined to said central waveguide section to receive microwave from said oscillator, a second rectangular waveguide branch perpendicular to said first branch, said second branch being coupled to said microwave inlet opening at one end thereof opposite to its joint to said central section, and a third rectangular waveguide branch collinear with said first branch, the outer end of said third branch opposite to its joint to said central section being closed, said first, second and third branches being branched from said central waveguide section at the H plane parallel to said side wall in three directions to form T-shaped configuration, at least one circular disc shaped ferrite element mounted on the inner surface of opposite broad side walls of said central waveguide section at a circularly polarized position, said ferrite element having a flat outer surface contacting said inner surface, means including an exciting element in the form of a disc shaped permanent magnet which is mounted on the outer surface of one of said broad side walls to oppose said ferrite element to supply thereto a magnetic field across said central waveguide section whereby to transmit the microwave in the forward direction into said heating cavity through said central waveguide section and through said first and second branches and to direct microwave reflected from said heating cavity toward said third branch and a microwave absorber provided in said third branch.

10. A microwave heating apparatus comprising a magnetron oscillator for supplying microwave energy, said oscillator having rod shaped antenna surrounded by a protective cover transmitted to microwave and adapted to extract and radiate generated microwave, a metal wall structure defining a substantially closed heating cavity and a waveguide connection including an H plane branched T-shaped waveguide interconnected by a central waveguide section having a rectangular cross section; a first rectangular waveguide branch, one end of said first branch on the side opposite to its other end joined to said central waveguide section being closed by a short circuiting end wall, a predetermined length between said closed end and said junction having relatively narrow width to form a branch section for coupling to said magnetron oscillator, remaining portion between said joint and said branch portion and contiguous thereto constituting another branch portion having the same width as the narrow side wall of said central waveguide section but shorter than said narrow side wall, said antenna of said oscillator extending into said branch section for coupling to said magnetron oscillator perpendicularly through an opening provided through one of said broad side walls of said waveguide, a second rectangular waveguide branch collinear with said first branch and coupled to said heating cavity on the side opposite to its junction to said central waveguide section, said second branch having substantially the same cross section as said branch section, and a third rectangular waveguide branch perpendicular to said first branch and having the same cross section as said branch section, the end of said third branch on the side opposite to its branched portion to said central waveguide section being closed, said first, second and third waveguide branches being branched from said central waveguide section at the H plane in these directions to form a letter T configuration, at least one circular disc shaped ferrite element mounted on the inner surface of a pair of opposing broad side walls of said cen-

tral waveguide section at a circularly polarized position, said ferrite element having a flat surface engaging said inner surface, means including an exciting element in the form of a disc shaped permanent magnet which is mounted on the outer surface of one of said broad side walls to oppose said ferrite element to supply thereto a magnetic field across said central waveguide section whereby to transmit the microwave in the forward direction into said heating cavity through said central waveguide section and through said first and second waveguide branches and to direct microwave reflected from said heating cavity toward said third branch and a microwave absorber provided in said third branch.

11. The microwave heating apparatus according to claim **10** wherein said antenna is provided at a position spaced from said short circuiting end wall by 11 mm. to 54 mm.

12. The microwave heating apparatus according to claim **10** wherein said antenna is provided at a position

spaced from said short circuiting end wall by 86 mm. to 128 mm.

13. The microwave heating apparatus according to claim **1** wherein said microwave absorber is tapered toward said central waveguide section.

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U.S. Cl. X.R.

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