

April 28, 1953

R. M. BAKER ET AL

2,636,975

HIGH-FREQUENCY HEATING APPARATUS

Filed June 26, 1948

2 SHEETS--SHEET 1

Fig. 1.

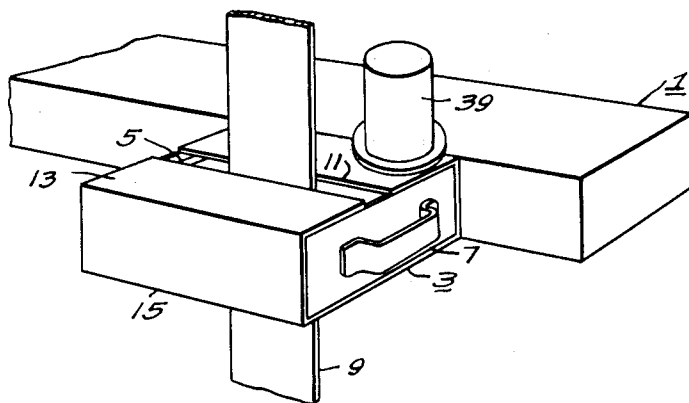
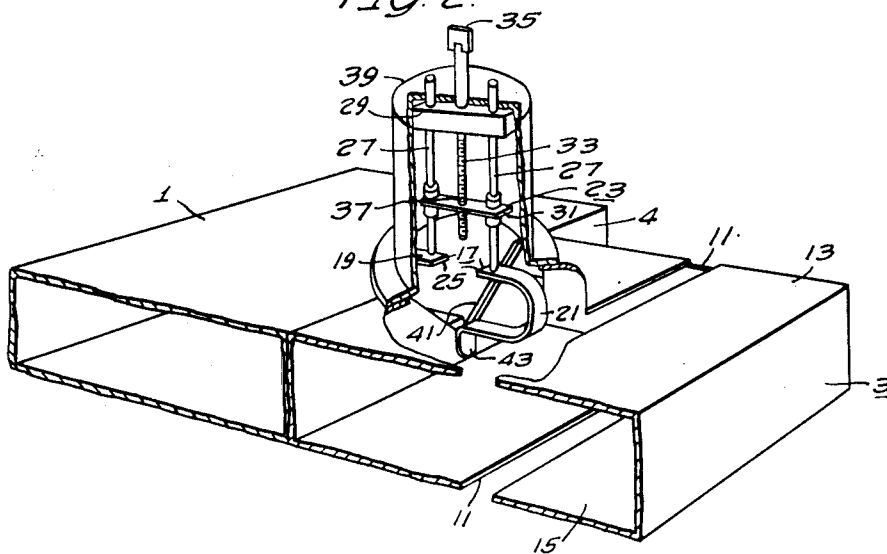


Fig. 2.



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2 SHEETS—SHEET 2

Fig. 3.

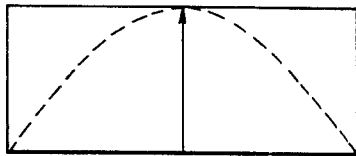
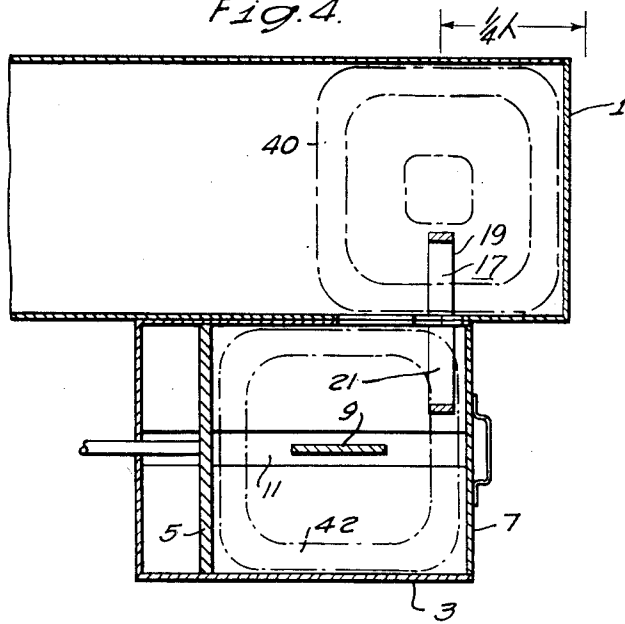


Fig. 4.



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## UNITED STATES PATENT OFFICE

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## HIGH-FREQUENCY HEATING APPARATUS

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6 Claims. (Cl. 219-47)

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This invention relates to high frequency electrical apparatus and particularly to apparatus for transferring high frequency electrical energy from a source to a load.

Ultra high frequency energy can be caused to flow along a hollow duct called a wave guide. The energy flowing in such a wave guide is manifested by electric and magnetic fields having a distribution and orientation depending on the mode of transmission. Such fields produce molecular friction in certain dielectric materials disposed in them, thereby heating the material. The energy in a wave guide may therefore be used for heating materials. In accordance with the teaching of the prior art of which we are aware, the material to be heated is inserted directly in the guide through a door in the end of the guide. Suitable tuning stubs are provided in such a guide, for matching the impedance presented by the load material to the impedance of the generator which supplies the energy flowing through the guide.

We have found that such prior art heaters are unsatisfactory for heating certain materials, particularly those dielectric materials which have relatively low loss factors, to the high temperature required in the industries in which the materials are used. The high frequency fields in a wave guide can also be impressed on a web of dielectric material drawn through the field to heat the web. We have found that such a web drawn through a wave guide must be moved relatively slowly to be properly heated.

It is accordingly an object of our invention to provide improved high frequency heating apparatus for heating materials to high temperatures.

It is also an object of our invention to provide a high frequency heating apparatus for quickly heating materials to high temperatures.

It is another object of our invention to provide a high frequency heating apparatus for quickly heating dielectric materials to high temperatures.

It is a further object of our invention to provide a high frequency heating apparatus for heating a web of material moved at high speed to high temperatures.

Our invention arises from the realization that the heat produced in dielectric material results from displacement current set up in the material by an electric field which varies with time. This displacement current increases as the electric field across the material is increased. In the practice of our invention a field having a

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high amplitude is accordingly impressed across the material to be heated.

In accordance with the broad aspect of our invention the material to be heated is disposed in a cavity coupled to a wave guide. The cavity is so coupled that the electric field produced in it is higher in amplitude than the field in the wave guide. The material to be heated is disposed in the strong portion of this higher amplitude field.

We have found that couplers in the prior art of which we are aware are not satisfactory for coupling a wave guide to a resonant cavity, due to difficulties encountered in tuning the coupler and arcing across the coupler parts, particularly whereas in the dielectric heating art, relatively large amounts of high frequency energy are involved.

It is therefore an ancillary object of our invention to provide an apparatus for efficiently coupling a wave guide to a resonant cavity.

It is also an ancillary object of our invention to provide a coupling arrangement between a wave guide and a resonant cavity wherein the cavity shall be driven at a voltage much higher than that in the wave guide.

Another ancillary object of our invention is to provide a coupler which can be mounted in its working position without the use of insulator supports.

Another ancillary object of our invention is to provide a high frequency coupler that can be conveniently tuned to half wave resonance.

A further ancillary object of our invention is to provide an improved coupler which shall be capable of handling relatively large amounts of high frequency energy.

A still further ancillary object of our invention is to provide an improved coupler construction wherein the effective inductance of the coupler loops shall be reduced to a value such that the coupler circuit can be conveniently tuned by an extended line.

In its specific aspects, our invention embraces two concepts—

First, the coupling of a wave guide to a resonant cavity by means of a tunable coupler which is capable of transferring relatively large amounts of high frequency electrical energy of the order in excess of one kilowatt, and which is tunable to half wave resonance so as to provide an efficient magnetic coupling between the wave guide and the resonant cavity, and obviate the use of insulator coupler mounting supports.

Second, the arrangement of a coupler be-

tween a wave guide and a resonant cavity so that one of its inductors links the maximum magnetic field of the wave guide and the other of its inductors links less than the maximum magnetic field of the resonant cavity, with the result that the cavity may be driven at a voltage much higher than that in the wave guide.

Our invention, together with additional objects and advantages thereof, will best be understood from the following description of one embodiment thereof when read in connection with the accompanying drawings, in which:

Figure 1 is a diagrammatic view in perspective showing a preferred embodiment of our invention.

Fig. 2 is a diagrammatic view in perspective showing in detail a portion of the apparatus shown in Fig. 1;

Fig. 3 is a graph showing the distribution of the maximum transverse electric field vector in a wave guide used in the practice of our invention; and

Fig. 4 is a sectional view taken on a horizontal plane through the apparatus of Fig. 2 showing magnetic field distribution.

The apparatus shown in Figs. 1 and 2 includes a rectangular wave guide, a resonant cavity, and a coupler, which are generally indicated by the reference numerals 1, 3 and 17 respectively. The wave guide 1 is of conventional construction and is connected to a suitable oscillator (not shown) such as a magnetron and is so coupled to this oscillator that the mode of propagation in the wave guide is  $TE_{01}$ . The wave guide 1 may be any convenient length and is closed at the end opposite the oscillator.

The resonant cavity 3 is a rectangular metal box preferably of the same width and height as the wave guide 1, and is closed by a tuning piston 5 at its end nearest to the wave guide power source. The other end of the resonant cavity 3 is closed by a door 7 to permit insertion and removal of certain materials to be heated. Openings 11 are provided in the top 13 and bottom 15 of the cavity 3 to allow passage of materials or articles 9 to be heated through the resonant cavity 3 when the apparatus is used in continuous treatment operation. In the specific embodiment shown in Fig. 1 these openings are in the form of elongated slots 11 and the material 9 being heated is shown passing through the slots 11 in the cavity 3 in web or ribbon form.

The coupler 17 comprises a pair of loop portions 19 and 21 and an extended line portion 23. The loop portions 19 and 21 may be made by bending a piece of a conductor in the form of two substantially horseshoe-shaped loops having a pair of spaced terminals 25 as shown in Fig. 2. The extended line portion 23 includes a pair of parallel conducting rods 27 which are attached at one end to the loop terminals 25 and supported near the other end by a metal bar 29. A short-circuiting bar 31 is slidably mounted upon the parallel conducting rods 27. A threaded shaft 33 having a tuning knob 35 on one end is rotatably mounted between the parallel conducting rods 27 so that its threaded portion engages a threaded hole 37 in the center of the short-circuiting bar 31. The position of the short circuiting bar 31 may be varied by turning the tuning knob 35. A cylindrical metal housing 39 is provided to shield and support the extended line portion 23 of the coupler 17.

The resonant cavity 3 and the wave guide 1 are juxtaposed as shown in Fig. 2. Corresponding

V-shaped slots 41 are cut in the adjacent sides of the wave guide 1 and cavity 3 and corresponding semicircular portions are cut away from their tops. The coupler 17 is placed symmetrically between the wave guide 1 and the resonant cavity 3 so that its loops 19 and 21 and extended line 23 are in a plane which passes through the vertex of the V-shaped slots 41 and is transverse to the axis of the wave guide 1. The extended line portion 23 of the coupler 17 extends up through the hole formed by the semicircular portions cut away from the tops of the wave guide 1 and cavity 3, and is covered by the cylindrical metal shield 39. The loop end of the coupler 17 is secured to the wave guide 1 and the cavity 3 at the vertex of the V-shaped slots 41, and the coupler 17 is supported at its other end by the cylindrical metal shield 39.

An important aspect of our invention relates to the positioning of the coupler loops 19 and 21 with respect to the wave guide 1 and resonant cavity 3 so that the field in the cavity 3 is high. Fig. 4 shows at a particular time the magnetic field intensity distributions in the wave guide 1 and the resonant cavity 3 in the vicinity of the coupler 17. The magnetic field 40 in the wave guide 1 is at a maximum intensity in the region near the side 4 and a quarter wave length from the end 2 of the wave guide 1. In order to make it possible to set up a maximum current in the coupler circuit, the loop of the coupler which extends into the wave guide must be located in the maximum magnetic field intensity region of the wave guide; therefore the vertex of the V-shaped slot 41 in the wave guide 1 is located at a point approximately a quarter wave length from the end of the guide 1 and the coupler 17 is mounted in the slot 41 as has been previously described.

The magnetic field in the wave guide induces a voltage in the wave guide coupling loop and causes alternating current to flow through the loop. This same alternating current flows around through the cavity loop and sets up a magnetic field at the cavity loop which is equal in intensity to that magnetic field at the loop in the wave guide. The magnetic field 42 in the resonant cavity 3 is at maximum intensity in the regions of the midpoints of the sides and ends of the cavity 3. The magnetic field intensity in the cavity 3 is at a minimum in the regions of the corners of the cavity. We mount the resonant cavity 3 in a position longitudinally of the wave guide 1 such that the door 7 of the cavity 3 is just under a quarter wave length from the end of the guide 1. This locates the coupler loop in the cavity 3 in a region of low magnetic field intensity in the cavity 3. The magnetic field intensity in the plane of the wave guide coupling loop 19 is of the same value as the magnetic field intensity in the plane of the cavity coupling loop 21. Proceeding from the cavity coupling loop to a distance one quarter wave from the end of the cavity it is found that the magnetic field intensity increases to a maximum value in the cavity due to the fact that the cavity has been tuned to resonance. Consequently the maximum field in the cavity is much higher than that in the wave guide.

An electric field proportional to the magnetic field occurs during that part of the cycle when magnetic energy has been transformed to electrical energy. Accordingly, an electric field is set up in the region of the center of the cavity 3 which is much greater than the electric field in

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the wave guide 1. The heating effect in a material disposed in an electric field depends upon the intensity of that field. Thus by using the apparatus in accordance with the teaching of our invention it is possible to heat materials more quickly and to higher temperatures than has been possible prior to our invention.

Referring now to Fig. 2, we will point out the specific features of the improved coupler which is used in the practice of our invention. In order to get an efficient transfer of energy from a wave guide to a cavity, there must be proper coupling between the wave guide and the cavity. To take care of variations in the frequency of the energy source it is desirable that the coupler be tunable. But in the field of dielectric heating, where quantities of high frequency electrical energy of the order in excess of one kilowatt are involved, peculiar problems arise in the construction of a satisfactory tunable coupler. We have found that a coupler comprising a pair of loops and an extended line is the most desirable. But in order to get a large amount of current induced in the coupler circuit it is necessary to make the loop in the wave guide large so that it links a large area of the magnetic field of the wave guide. However in making the loop large, its effective inductance would ordinarily be increased to a value such that it could not be tuned by a reasonable length of extended line. However, we overcome this difficulty by specially constructing the loops in a manner which will be hereinafter described. A maximum transfer of energy between the wave guide 1 and the cavity 3 is obtained when the circuit consisting of the coupler loops 19 and 21, the extended line 23, and the short-circuiting bar 31 is tuned to half-wave resonance. In other words, when there are voltage nodes at the point 43 where the loops 19 and 21 are attached to the wave guide 1 and cavity 3, and at another point an effective half wave length in either direction from the first point. Now if the effective inductance of the loop 19 in the wave guide 1 is so large that it takes a length of extended line 23 the same length or longer than the physical length of the loop 19 to tune it, a voltage anti-node in the coupler circuit will appear near the loop terminal 25 or out on the extended line 23 and arcing will occur at the loop terminals 25 or on the extended line 23. Therefore it is necessary to construct a coupler loop 19 which has a large area and at the same time an effective inductance low enough to be tunable by a section of extended line 23 whose length is shorter than that of the loop 19, in order that the voltage peak of the coupler circuit will not occur near the loop terminal 25 or out on the extended line 23. To decrease the effective inductance of the coupler loop 19 to a value which is tunable by a section of extended line 23 shorter than the loop 19, and at the same time keep the loop area large, we make the width of the loop large in comparison to its thickness. A loop width of the order of 16 times the thickness is satisfactory.

When the coupler loops 19 and 21 are made the same size and the coupler circuit is tuned to half wave resonance, voltage nodes will occur at the point where the loops 19 and 21 are attached to the wave guide 1 and cavity 3 and near the center of the short-circuiting bar 31. This means that the portion of the extended line 23 which is above the short-circuiting bar may be directly attached to the cylindrical housing 39, whereby the coupler is supported entirely without the use of insulators which may be destroyed by being

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subjected to the dielectric heating effects of the intense electric fields encountered during the use of the coupler. Thus we have constructed a coupler capable of transferring large amounts of high frequency energy without arcing and tunable to half-wave resonance so as to get a maximum energy transfer between a wave guide and a resonant cavity, and obviate the use of lossy dielectric insulators in mounting the coupler.

In the operation of the apparatus, the material 9 to be heated is placed in the center of the resonant cavity 3, and electrical energy at a suitable high frequency, for example 430 mc., is fed into the wave guide 1. Then the cavity 3 is tuned to resonance by means of its tuning piston 5, and the coupler circuit is tuned to half-wave resonance by means of the coupler tuning knob 35.

The operating frequency or the arrangement of the material 9 to be heated in the cavity 3 may be varied to suit the purpose at hand.

Although we prefer to make the coupler loops 19 and 21 the same size, their relative sizes may be varied somewhat without departing from the scope of our invention. The relative position of the cavity 3 with respect to its coupler loop 21 may be varied so as to get the desired increase in electric field intensity over that in the wave guide 1.

Although we have described the operation of our invention as it is applied in the dielectric heating art, we do not wish to be limited to that application.

Our invention can be applied wherever it is desired to transfer appreciable amounts of high frequency electrical energy from a wave guide to a resonant cavity.

By the expression cavity resonator we intend to mean a cavity, usually metallic and having conductive walls, in which ultra high frequency electromagnetic oscillations can exist when the cavity is properly excited; its resonant frequency is determined by its physical dimensions. By the expression coupler or coupling element we intend to mean apparatus or means by which energy is transferred from one circuit to another; the common impedance necessary for effecting such coupling. By the expression wave guide we intend to mean a hollow pipe-like conductor of electromagnetic energy which is used as a radio frequency transmission line; its dimensions are determined by the wave length of the electromagnetic energy to be transmitted.

Our invention, therefore, is not to be restricted except in so far as is necessitated by the prior art and by the spirit of the appended claims.

We claim as our invention:

1. For heating a dielectric material, a wave guide, a resonant cavity adapted to receive a dielectric material to be heated and a coupler tunable to half wave resonance comprising an extended line portion and two loop portions, said coupler being placed longitudinally of the wave guide so that one of said loop portions links the maximum magnetic field of the wave guide, said resonant cavity being placed adjacent the wave guide in a position longitudinally of the wave guide such that the other of said loop portions links less than the maximum magnetic field of the said resonant cavity.

2. For heating dielectric material, a rectangular wave guide having common openings in its side and top, a resonant cavity having like openings in its side and top and placed adjacent the wave guide so that said openings are aligned, a coupler comprising two loop portions and an

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extended line portion and placed between the wave guide and the cavity so that said loop portions are attached to the bottom of the said side openings and the extended line portion extends up through the said top openings, and a metal housing placed over said top openings so as to shield and support said extended line.

3. For heating dielectric material, a rectangular wave guide having a V-shaped slot in its side and a semicircular slot whose diameter is in the plane of the V-shaped slot in its top, a resonant cavity having like slots in its side and top and placed adjacent the wave guide so that said V-shaped slots are aligned, a coupler comprising a pair of loops and an extended line which is bridged by a slidable short-circuiting bar, said coupler being attached at its loop end to the vertex of said V-shaped slots so that one loop extends into the wave guide and the other loop extends into the resonant cavity and the extended line protrudes up through the opening formed by said semicircular slots, a shielding housing placed over said opening to enclose and support said extended line, and a threaded shaft extending through the top of said housing and engaging the slidable short-circuiting bar of said extended line, said threaded shaft being rotatable by means of an external knob to tune said coupler.

4. For coupling a hollow wave guide to a structure forming a resonant cavity, a coupler circuit tunable to half wave resonance comprising that portion of an adjustable extended line which consists of two conducting rods bridged by a slider bar, and a pair of loops, adapted to be inserted one into the wave guide and the other into the cavity, joined at one of their ends and having their other ends spaced apart, said conducting rods being connected to the spaced ends of the loops, the width of said loops being large as compared to their thickness, whereby their effective inductance is reduced to a value which can be tuned by a section of extended line whose length is less than the physical length of one of said loops.

5. A coupling device for use between a resonant cavity and a load and tunable to half wave resonance and capable of handling amounts of high frequency electrical energy of the order in excess

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of one kilowatt, comprising a pair of oppositely disposed low inductance loops having one of their ends joined and the other of their ends spaced, one of said loops being positioned to be responsive to electrical energy in said cavity and the other of said loops being positioned to feed electrical energy to said load, an extended line section attached to said spaced ends, a short-circuiting slider mounted upon said extended line for tuning the circuit composed of the loops, the extended line and the slider to half wave resonance.

6. For use in heating materials, a wave guide, a resonant cavity adapted to receive material to be heated, and a coupler tunable to half wave resonance comprising a pair of oppositely disposed loops having one of their ends joined and the other of their ends spaced, and parallel conducting rods bridged by a short-circuiting slider bar attached to said spaced ends, said coupler being placed so that one of its loops extends into the wave guide and the other of its loops extends into the cavity, said coupler being supported between the wave guide and the cavity from its portion where the loop ends are joined and its portion which is above the short-circuiting slider; each of said supporting portions of the coupler being attached to its supporting member.

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