

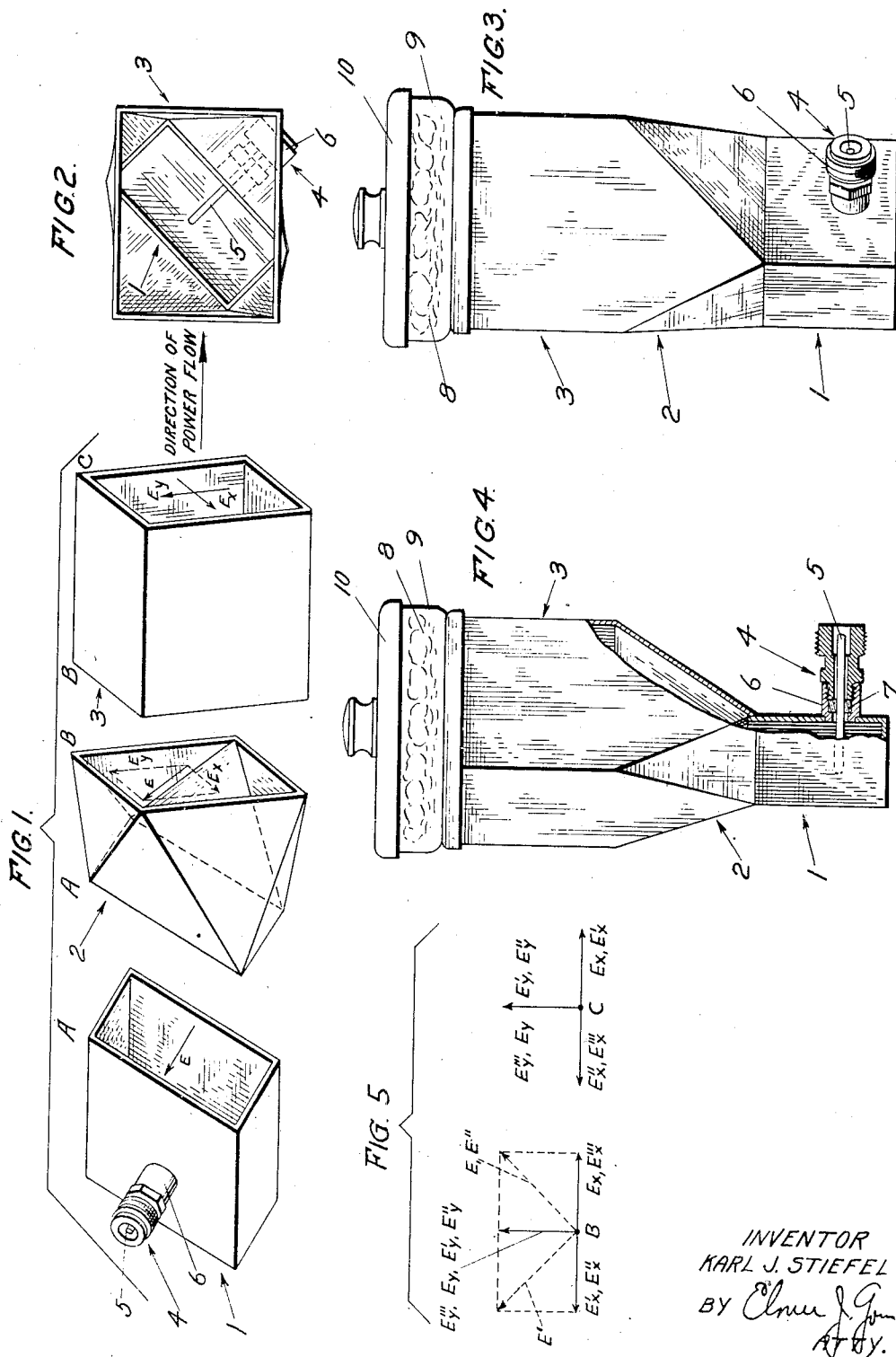
Aug. 30, 1949.

K. J. STIEFEL
MICROWAVE HEATING APPARATUS USING
CIRCULARLY POLARIZED HORN

2,480,682

Filed Sept. 21, 1946

2 Sheets-Sheet 1



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FIG. 6

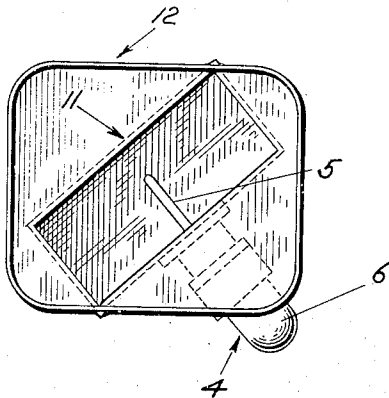


FIG. 7

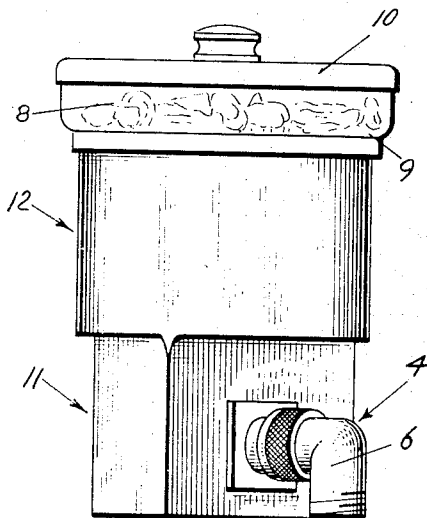
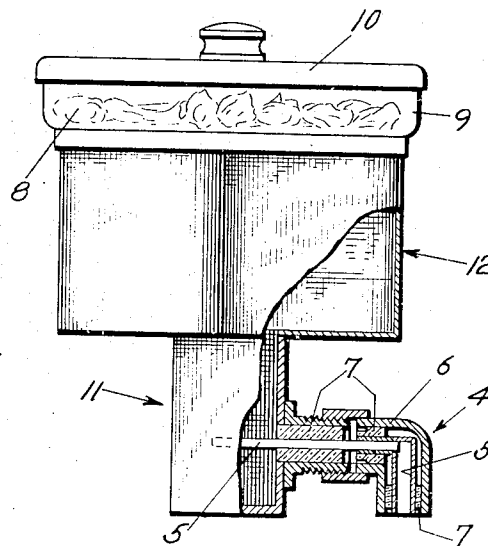


FIG. 8



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MICROWAVE HEATING APPARATUS USING
CIRCULARLY POLARIZED HORNKarl J. Stiefel, Waltham, Mass., assignor to Raytheon Manufacturing Company, Newton, Mass.,
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8 Claims. (Cl. 219-47)

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This invention relates to high-frequency apparatus, and more particularly to apparatus for heating dielectric substances by the passage of high-frequency energy therethrough, or by the application of high-frequency energy thereto.

An object of this invention is to provide apparatus by the use of which substantially uniform ultra-high-frequency heating of a body may be accomplished.

Another object is to devise apparatus for obtaining a maximum power output from a high-frequency source.

A further object is to devise apparatus for reducing the standing wave ratio in a high-frequency system, whereby the high-frequency source will be protected from the normally-high-amplitude standing waves.

A still further object is to reduce the standing wave ratio in a high-frequency system, whereby the efficiency of the high-frequency source is increased.

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

Fig. 1 is an exploded isometric view of one embodiment of the invention;

Fig. 2 is a top plan view, with the load removed, of the assembled device of Fig. 1;

Fig. 3 is a front elevation of Fig. 2, the device being shown in use for heating;

Fig. 4 is a front elevation of the device looking at an angle of 45° from Fig. 3;

Fig. 5 is a vector diagram useful in explaining the operation of the device;

Fig. 6 is a top plan view, with the load removed, of another embodiment of the invention.

Fig. 7 is a front elevation of Fig. 6, the device being shown in use for heating; and

Fig. 8 is a front elevation of the device of Fig. 6, looking at an angle of 45° from Fig. 7.

In describing my invention, which involves the use of elliptically-polarized, and more particularly circularly-polarized, waves for dielectric heating, I will first define what is meant by circular polarization. An electrical wave is said to be circularly polarized when the field thereof can be resolved into two equal components 90° apart in space and 90° apart in time. If the two vectors are not of equal amplitude, or if the time difference between them is other than 90°, the wave is said to be elliptically polarized; in the special case in which the time phase angle reduces to zero, the wave is linearly polarized. In other words, both

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linear polarization and circular polarization can be looked upon as special cases of elliptical polarization. This last statement can be demonstrated mathematically as follows:

First, we start with two electric vectors 90° apart in space with an arbitrary phase difference δ . These vectors may be represented as follows:

$$E_y = B \cos(\omega t - \beta x + \delta) \quad (1)$$

$$E_x = A \cos(\omega t - \beta x) \quad (2)$$

Substituting $u = \omega t - \beta x$ in the expressions for E_x and E_y , we have

$$E_x = A \cos u \quad (3)$$

$$E_y = B \cos(u + \delta) = B(\cos u \cos \delta - \sin u \sin \delta) \quad (4)$$

From (3),

$$\cos u = \frac{E_x}{A}$$

from which it follows that

$$\sin u = \sqrt{1 - \left(\frac{E_x}{A}\right)^2} \quad (5)$$

Substituting for $\cos u$ and $\sin u$ in (4),

$$\frac{E_x \cos \delta}{A} - \frac{E_y}{B} = \sqrt{1 - \left(\frac{E_x}{A}\right)^2} \sin \delta \quad (6)$$

Squaring both sides and simplifying,

$$\frac{E_x^2}{A^2} + \frac{E_y^2}{B^2} - \frac{2E_x E_y \cos \delta}{AB} = \sin^2 \delta \quad (7)$$

This is the equation of an ellipse, and the wave is said to be elliptically polarized.

If

$$\delta = \frac{\pi}{2}$$

(components 90° apart in time phase) and $A=B$ (components of equal amplitude), (7) reduces to

$$E_x^2 + E_y^2 = A^2 \quad (8)$$

which is the equation of a circle. The wave is then circularly polarized.

If $\delta=0$ or π (components in phase or 180° out of phase), Equation 7 becomes that of a straight line and the wave is linearly polarized.

Thus we see that, mathematically, elliptical polarization is the general case when two waves are combined, and that circular and linear polarization are special cases; this is similar to the situation mentioned in elementary geometry in which it is demonstrated that the circle and the straight line are the limiting forms of an ellipse.

Referring, now, to Fig. 1, an exploded view of a device for converting a linearly-polarized wave into a substantially-circularly-polarized wave is

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shown, said device consisting of a hollow rectangular metallic wave guide 1 open at one end and having a horn coupled to said open end, said horn comprising a hollow metallic transition member 2, open at both ends, and a hollow substantially square metallic wave guide 3, also open at both ends. The guide 3 is rotated substantially 45° with respect to guide 1, so that the walls of guide 3 lie at an angle of substantially 45° to the respective walls of guide 1, the center lines of said guides being collinear (or said two guides being joined axially to each other) and the transition member 2 joining the open end of guide 1 rigidly to the contiguous end of guide 3; guides 1 and 3 are of constant cross-section throughout their lengths while member 2 has a constantly varying cross-section throughout its length, in accordance with its transition function. The opening at one end of transition member 2 has the same area as the open end of guide 1 and matches said open end, while the opening at the other end of said transition member has the same area as the contiguous open end of guide 3 and matches said open end. One cross-sectional dimension of guide 1 may, for example, be twice the other; for example, guide 1 may be a standard one-and-a-half inch by three-inch guide.

A coaxial line 4, consisting of an inner conductor 5 supported coaxially in an outer hollow conductor 6 by dielectric spacing means such as 7, has its outer conductor 6 attached to the exterior central portion of one of the wider side walls of guide 1 near the closed end of said guide, the coaxial line extending at right angles to said side wall. Inner conductor 5 projects through an opening in said side wall into the interior of the guide 1 for a substantial distance, for example, approximately two-thirds of the distance to the opposite side wall. The free end of coaxial line 4 is adapted to be connected to the output pipe or lead of a source of high-frequency energy, for example, a magnetron.

The end of inner conductor 5 projecting inside the guide, which may for convenience be termed the exciting rod, is spaced a distance of a quarter wavelength (in the guide) from the closed end of said guide. When a high-frequency continuous wave, having a wavelength on the order of 10 centimeters for example, is supplied to guide 1 by means of line 4, a wave having a $TE_{0,1}$ mode is set up in said guide. With such a wave, the electric vector E, at the output end A of guide 1, is perpendicular to the longer side walls, or the wider faces, of said guide, so that the wave produced at A is linearly polarized; this linearly-polarized wave is applied to the input end A of transition member 2. Due to the substantially 45° rotation of guide 3 with respect to guide 1, at the output end B of transition member 2 (or the input end B of guide 3), vector E, which at A was perpendicular to the wide faces of rectangular guide 1, now appears across diagonal corners of the substantially square guide 3. Of course, because guide 3 is not exactly square, variation of the relative angle of rotation of guides 1 and 3, from 45°, may be made to make certain that vector E, at B, will lie along the diagonal of guide 3. This diagonal vector E can be considered as the resultant of two equal vectors, one perpendicular to each respective pair of faces of the square guide 3. Therefore, we can think of two waves of equal amplitude propagating down the square guide 3, one characterized by an electric vector E_x perpendicular to one pair of opposite

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walls of said guide and the other, E_y , perpendicular to the other pair of opposite walls. Therefore, the first step in converting a linearly-polarized wave into a circularly-polarized wave, which is to split the linearly-polarized wave into two equal components at 90° to one another, has been accomplished when the wave reaches B.

Two vectors of equal amplitude 90° apart in space exist at the output end B of the transition member or wave splitter 2; however, vectors E_x and E_y are still in time phase and the resultant is a linearly-polarized wave, since Equation 7 degenerates into that of a straight line when $\delta=0$. The only other condition to satisfy for circular polarization is to make $\delta=90^\circ$ or 270° , either value reducing (7) to the equation of a circle.

In the discussion above, the nearly square guide 3 has been assumed square for all practical purposes in saying that the wave splits into two equal components. Actually, the magnitude of the two components will be slightly different, but not enough to be more than a second-order effect; the reason for making guide 3 not quite square will become apparent.

The wave guide 3 as seen by the component E_x is a little different in width from that seen by E_y . Therefore, their velocities of propagation are somewhat different, and in the passage from B down the nearly square guide 3 the phase angle δ between E_x and E_y progressively departs from zero and the wave becomes elliptically polarized; at some point C, the phase difference reaches 90° and the resultant wave is substantially circularly polarized. The substantially square wave guide 3 is terminated at point C whereby the radiated wave is substantially circularly polarized.

Of course, it is impossible, as a practical matter, to produce exact circular polarization of the wave at point C. This can be seen from the fact that, in order for the component vectors E_x and E_y to be of equal amplitude, wave guide 3 must be of exactly square cross-section; however, if guide 3 is exactly square, the phase angle between E_x and E_y can never be changed from zero and therefore can never be brought to the 90° phase angle necessary for circular polarization. However, by proper dimensioning and positioning of the guides, it is possible to obtain substantially circular polarization of the waves, and, as will be pointed out hereinafter, the advantages of this invention are obtainable with waves having merely a substantial degree of elliptical polarization (as contrasted to linearly-polarized waves), as well as with waves having true circular polarization.

If desired, the device may be terminated by another hollow, horn-like section (not shown) which converts from a nearly square throat (at C) to a circular aperture. This accomplishes an impedance match to space from the substantially square guide, but is not essential to the generation of a circularly-polarized wave.

It is obvious, from the above discussion, that true circular polarization occurs at only one frequency, and that the wave becomes elliptically polarized at either side of this frequency. However, with proper design the variation from true circular polarization with frequency may be made sufficiently low to permit operation over a rather wide frequency range, since the advantages of the invention are obtainable with waves having a substantial degree of elliptical polarization.

In the device as used for dielectric heating, as shown in Figs. 3 and 4, the dielectric material 8 to be heated or defrosted, such as food for ex-

ample, is supported, by a suitable dielectric supporting means 9, adjacent the free end of wave guide or horn 3. A metallic cover 10, which acts as a reflector of electromagnetic waves, is placed adjacent material 8, on the side thereof opposite from guide 3.

The material 8, together with cover 10, acts as a partially absorbing and partially reflecting medium. I have found that, with a substantial degree of elliptical polarization, as well as with circular polarization, of the wave, the standing wave ratio in the energy feed line is less than with linear polarization, when the energy is used for heating a partially absorbing and a partially reflecting medium. When the standing wave ratio in a high-frequency feed line is low, a maximum amount of power may be obtained from a high-frequency source such as a magnetron, and, with a reduced standing wave ratio, the efficiency of the source is increased. Also, a high standing wave ratio may cause rapid deterioration of the high-frequency source.

Let us define the electric field of the wave at B by the equations

$$E_x = \frac{E}{\sqrt{2}} \cos(\omega t - \beta_1 x), \quad (9)$$

and

$$E_y = \frac{E}{\sqrt{2}} \cos(\omega t - \beta_2 x) \quad (10)$$

rene, and from 30 to 45 per cent of acronitrile.

Let us further assume that the length and dimensions of the phasing section of guide 3 are such that the component E_x suffers a progressive phase change of 2π from B to C, and that $\beta_2 = \frac{3}{4}\beta_1$.

Therefore at C, the wave has the components

$$E_x = \frac{E}{\sqrt{2}} \cos(\omega t - 2\pi) \quad (11)$$

and

$$E_y = \frac{E}{\sqrt{2}} \cos\left(\omega t - \frac{3}{2}\pi\right) \quad (12)$$

which yield a circularly-polarized wave since the components are 90° apart in time and space, assuming the components to be equal in amplitude.

Now let us assume that the wave impinges upon an absorbing means which partially absorbs and partially reflects the incident energy. The reflected wave components will be altered in time phase in some manner dependent on the properties of the absorbing medium although the space relationship of the components will stay the same. We can merely say for our purpose here that the time phase of each component is shifted on reflection by an arbitrary angle ϕ .

Then, the reflected wave may be written as follows where α =per cent reflection of the incident wave:

$$E_x = \frac{\alpha E}{\sqrt{2}} \cos(\omega t - 2\pi + \phi + \beta_1 x) \quad (13)$$

$$E_y = \frac{\alpha E}{\sqrt{2}} \cos\left(\omega t - \frac{3}{2}\pi + \phi + \beta_2 x\right) \quad (14)$$

By the time the reflected wave has arrived at B, it has again been retarded as before (E_x retarded by 2π and E_y by $\frac{3}{2}\pi$), so at B, the reflected wave has the components:

$$E_x = \frac{\alpha E}{\sqrt{2}} \cos(\omega t - 4\pi + \phi) \quad (15)$$

$$E_y = \frac{\alpha E}{\sqrt{2}} \cos(\omega t - 3\pi + \phi) \quad (16)$$

which may be written

$$E_x = \frac{\alpha E}{\sqrt{2}} \cos(\omega t + \phi) \quad (17)$$

$$E_y = \frac{\alpha E}{\sqrt{2}} \cos(\omega t \pm \pi + \phi) = -\frac{\alpha E}{\sqrt{2}} \cos(\omega t + \phi) \quad (18)$$

The minus sign for E_y may be looked upon as a space reversal of the vector E_y . This means that the resultant of these two vectors (they are now shown to be back in time phase) is at right angles to the initial vector E .

If the wave guide 1 has a cross-section of $1\frac{1}{2}$ inches by 3 inches, the critical wavelength for a TE_{01} wave whose electric vector is perpendicular to the 3-inch side is 2×3 , or 6 inches, which is approximately 15 centimeters; the critical wavelength for a TE_{01} wave whose electric vector is perpendicular to the $1\frac{1}{2}$ inch side is $2 \times 1\frac{1}{2}$, or 3 inches, which is approximately $7\frac{1}{2}$ centimeters. This is true because, as is well-known to those skilled in the art to which this invention relates, the critical wavelength for a TE_{01} (or H_{01}) wave being transmitted through a rectangular wave guide is equal to twice the dimension of the guide to which the electric vector of the wave is perpendicular. In other words, the longest wave that can be transmitted in the waveguide 1 has a half-wavelength in air equal to or less than the dimension of the guide normal to the direction of the electric vector of the wave. Therefore, a wave whose wavelength is greater than 15 cm. will not be propagated in guide 1 at all; one whose wavelength lies between $7\frac{1}{2}$ and 15 cm. will be propagated in said guide when the electric vector thereof is perpendicular to the wider face of the guide but not when the electric vector is perpendicular to the narrower face of the guide; one whose wavelength is less than $7\frac{1}{2}$ cm. will be propagated in said guide when its electric vector is perpendicular to either the wide or the narrow faces of the guide 1. As long as the dimension a normal to the direction of the electric vector is equal to or greater than the half-wavelength in air, the "characteristic" impedance of the guide is real and positive, a necessary condition for the propagation of wave energy. This is expressed by the equation for the characteristic impedance Z for the TE_{01} mode:

$$Z = \sqrt{\frac{\mu}{\epsilon}} \frac{1}{\sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2}} \quad (18a)$$

Since

$$\sqrt{\frac{\mu}{\epsilon}}$$

is real and positive, then Z is real and positive as long as $\lambda_0 < 2a$.

If a guide capable of supporting the TE_{01} mode is joined to a guide whose dimension a normal to the direction of the electric vector is too small to support propagation of energy at the wavelength being used, or in which $\lambda_0 > 2a$, then the wave energy incident upon this junction will be reflected because the waveguide impedance beyond the junction is no longer real and positive, but is imaginary. This is true because the term

$$\frac{\lambda_0}{2a}$$

in Equation 18a becomes greater than one, and the entire expression becomes imaginary. In other words, the wave strikes an extreme impedance discontinuity and is reflected.

As stated above, a wave having a wavelength λ_0 of ten centimeters is used in this invention, which means that $\lambda_0 > 2a$ when the electric vector is perpendicular to the shorter or $1\frac{1}{2}$ -inch side of the rectangular guide 1. Therefore, this wave is capable of being propagated in guide 1 only when the electric vector thereof is perpendicular to the wider face of said guide, as is vector E in Fig. 1; if said vector is at right angles to E in Fig. 1, the wave is not capable of propagation in guide 1, but is reflected at the junction A between said guide and a guide 2 which is capable of propagating such a wave mode, as discussed above in connection with Equation 18a.

As described above, with reference to Equation 18, the resultant of the two vectors E_x and E_y , after reflection, is at right angles to the initial vector E. Therefore the reflected wave cannot propagate along guide 1; the wave is therefore reflected back again, suffers attenuation from another passage through the absorbing material, and on the second reflection from the absorber is free to propagate along rectangular guide 1 and return to the source, since the minus sign of Equation 18 becomes positive on the second reflection so that the resultant at this time is in the original direction E of Fig. 1.

The above action can be more clearly explained by reference to Fig. 5, which represents, at B and C, respectively, the space relationships of the electric component vectors at points B and C. At point B, as described above, the component vectors E_x and E_y of the wave, as supplied by the source and as split by the wave splitter 2, are 90° apart in space as shown and their resultant has the direction of E at this time; the space relationship of these vectors is not changed by passage through horn or guide 3, so that at point C, the mouth of the horn, the components E_x and E_y are also 90° apart in space as shown.

It is assumed that there is a 180° phase shift in the wave during the passage of said wave from point C, through load 8 to reflector 10 and back through load 8 to point C, so that $\phi = \pi$ in Equations 17 and 18. Therefore, from said equations, at point B the reflected wave has the components:

$$E_x = \frac{\alpha E}{\sqrt{2}} \cos(\omega t + \pi) = -\frac{\alpha E}{\sqrt{2}} \cos \omega t \quad (19)$$

$$E_y = \frac{\alpha E}{\sqrt{2}} \cos(\omega t \pm \pi + \pi) = \frac{\alpha E}{\sqrt{2}} \cos \omega t \quad (20)$$

The wave represented by components E_x and E_y is applied to the load 8, being attenuated thereby, from whence it passes to the reflector 10, which reflects it back through the load toward the source, in the same direction, as E_x' and E_y' .

When the reflected wave reaches point B, as shown above by Equations 19 and 20, the component E_x' is reversed in space with respect to its original position E_x , as is indicated by the minus sign for E_x in Equation 19; also, when two vectors are 180° apart in time, they reach their maxima simultaneously, but in opposite directions, so that, if said vectors are originally 90° apart in space, this 180° phase difference is equivalent to a space reversal of one of them. Therefore, E_x' has the direction shown at B in Fig. 5. This means that the resultant E' of E_x' and E_y' at the bottom B of the horn 3 is turned 90° from its original position E when it entered phasing section or horn 3; therefore this reflected wave E' cannot enter the rectangular guide 1 toward the source since its wavelength is greater than the critical wavelength for propagation in this direc-

tion down guide 1; the reflected wave E' is therefore reflected from end A of the source feed line 1 back toward load or body 8 as components E_y'' and E_x'' , assuming no space shift of these vectors at this reflection.

This reflected wave reaches point C with the component directions E_y'' and E_x'' , and again passes through load or body 8 to reflector 10, from which the remaining unattenuated portion of the wave is reflected back toward the source, through point C, as components E_x''' and E_y''' , which are in the same direction as E_x'' and E_y'' , respectively. When this reflected wave, after its second roundtrip through body 8, again reaches point B, the vector E_x''' is again reversed in space with respect to its former position E_x'' , since the minus sign of Equation 19 becomes positive on the second reflection. Therefore E_x''' has the position shown at B.

The resultant E'' of E_x''' and E_y''' at the bottom B of the horn 3 is in the same direction as the original resultant E, so that this remaining unattenuated portion of the original wave can propagate down guide 1, proceeding to and beyond point A of guide 1 to the source itself, setting up standing waves in the feed line 1.

It is thus apparent that, by the use of circularly-polarized waves, no wave energy will be reflected back to the source until the original wave has made two complete roundtrips through the body or load 8; during these two roundtrips the high-frequency energy of the source is highly attenuated by said body, giving substantially uniform heating of said body due to the two roundtrips of the wave therethrough. In a test of a device using circularly-polarized waves, measurements showed that the food 8 absorbed about 65 per cent of the high-frequency power one way; however, after two reflections of the wave, only 1.5 per cent of the total power remained unabsorbed. It is therefore apparent that, with this invention, a maximum power output may be obtained from a high-frequency source of any given capacity; therefore the efficiency of the system is increased.

Although, in the above discussion, particular reference has been made to circular polarization, this has been done only for purposes of illustration; the advantages of the invention are also obtainable with waves having a substantial degree of elliptical polarization, as contrasted to linearly-polarized waves. For example, if the two components E_x and E_y of the wave are unequal in amplitude, the wave is elliptically polarized. In this case, the greater of the two vectors may be considered to be made up of two collinear vectors, one having a magnitude equal to that of the other orthogonally-related vector; and the second having a magnitude which is that of the total vector minus said one vector. Said one vector and its orthogonally-related mate give a wave which is circularly polarized, and which makes two roundtrips through the load, as described above, before being reflected back to the source; the remainder of the larger of the two orthogonally-related vectors acts as a linearly-polarized or plane-polarized wave, travelling back to the source after its first roundtrip through the load, thereby creating standing waves in the high-frequency feed line.

Therefore, with waves having a substantial degree of elliptical polarization the advantages of this invention are obtained, since with such waves a substantial portion of the reflected waves, and therefore also a substantial portion of the stand-

ing waves, are eliminated or attenuated by the load. It is apparent, from the above discussion, that the maximum reduction of standing waves in the feed line is obtained with waves having true circular polarization; somewhat less of a reduction of the standing wave ratio is obtained with elliptically-polarized waves, this reduction getting less the closer we get to linear or plane polarization, becoming zero if a linearly-polarized or plane-polarized wave is used—that is, relatively high standing waves are produced with plane polarization due to the single roundtrip of such waves through the load, as contrasted with the relatively low standing waves produced when waves having a substantial degree of elliptical polarization are used, due to the two roundtrips of such waves (or a portion thereof) through the load.

In the preceding discussion, it has been assumed that there is a phase shift of 180° in the load, material, or body 8. It will be apparent that, if this load phase shift differs from 180° , the wave may be reflected back and forth through the load 8 three, four, or even more times before the components of the reflected wave will have such space relationship that they can be combined to give a resultant vector which is in the direction of E in Fig. 1.

By the use of this invention, using waves having a substantial degree of elliptical polarization, the standing wave ratio is much smaller than if a linearly-polarized system were used. The standing wave voltage ratio, for linear polarization, is

$$S. W. V. R. = \frac{1+\alpha}{1-\alpha} \quad (21)$$

For circular polarization, this becomes

$$S. W. V. R. = \frac{1+\alpha^2}{1-\alpha^2} \quad (22)$$

For example, if $\alpha=20$ per cent reflection, then for linear polarization the standing wave ratio would be 1.5, but for circular polarization only 1.08; this would mean much more favorable conditions for the power source, particularly for large values of α which occur in heating work. By the reduction of the standing wave ratio in a high-frequency system, the high-frequency source is protected from large standing waves and the efficiency of the high-frequency source is increased. Since the sum of the incident and reflected waves produces standing waves, and since with this invention the reflected waves have a minimum amplitude as a result of their high attenuation during two roundtrips through the absorbing medium, it is apparent that minimum standing waves are set up in the high-frequency system feed line.

Figs. 6-8 show another embodiment of the invention; this embodiment also is a high-frequency heating device which converts a linearly-polarized wave into a wave having a substantial degree of elliptical polarization, and in which said elliptically-polarized wave is passed through the dielectric body to be heated, the attenuation of said wave by said body serving to heat said body. A hollow rectangular metallic wave guide 11, open at one end, has its open end directly and rigidly joined to a horn 12, said horn comprising a hollow substantially square metallic wave guide open at one end and having an opening at its opposite end of the same area as the open end of guide 11, said opening matching said open end. The

guide or horn 12 is rotated substantially 45° with respect to guide 11, so that the walls of guide 12 lie at an angle of substantially 45° to the respective walls of guide 11, the center lines of said guides being collinear (or said two guides being joined axially to each other); guides 11 and 12 are of constant cross-section throughout their lengths. One cross-sectional dimension of guide 11 may, for example, be twice the other; for example, guide 11 may be a standard one-and-a-half-inch by three-inch guide.

A coaxial line 4, consisting of an inner conductor 5 supported coaxially in an outer hollow conductor 6 by dielectric spacers such as 7, has its outer conductor 6 attached to the exterior central portion of one of the wider side walls of guide 11 near the closed end of said guide, the coaxial line extending at right angles to said side wall. Inner conductor 5 projects through an opening in said side wall into the interior of the guide 11 for a substantial distance, for example, approximately two-thirds of the distance to the opposite side wall. The free end of coaxial line 4 is adapted to be connected to the output pipe or lead of a source of high-frequency energy, for example, a magnetron.

The end of inner conductor 5 projecting inside the guide 11, as in Fig. 1, is spaced a distance of a quarter wavelength (in the guide) from the closed end of said guide, so that when a high-frequency wave whose wavelength is on the order of 10 cm., for example, is supplied to guide 11 by means of line 4, a linearly-polarized wave having a $TE_{0,1}$ (or H_{01}) mode is set up in said guide. As described above, in connection with Fig. 1, in order to convert a linearly-polarized wave into a substantially circularly-polarized wave, it is necessary to resolve the vector representing the original wave into two components 90° apart in space and 90° apart in time. In the embodiment of Figs. 6-8, the wave splitter, or transition member between the rectangular guide and the substantially square guide, is omitted, as will be seen. In this second embodiment, the original vector is split, or resolved into two components at 90° to each other, at the plane of the junction between the two guides 11 and 12, which plane would correspond to point B in Fig. 1. This splitting is caused by the substantially 45° rotation of guide 12 with respect to guide 11, together with the substantially square cross-section of guide 12, so that the original electric vector lies along the diagonal of guide 12. Then, as the wave travels to the end of the horn or phasing section 12, the two orthogonally-related component vectors are caused to have a 90° phase relation to each other, so that at the end of guide 12 remote from guide 11, a circularly-polarized wave appears. This phase shift along guide 12 is in accordance with the principles stated above for the phasing section or substantially square wave guide 3 of Fig. 1.

Here, as in Fig. 1, the length and the cross-sectional dimensions of the substantially square wave guide are made such that the phase change between the two components E_x and E_y (from end to end of the guide) is 90° or 270° , and such that the two components E_x and E_y are substantially equal in magnitude.

In the device as used for dielectric heating, as shown in Figs. 7-8, the dielectric material 8 to be heated or defrosted, such as food for example, is supported, by a suitable dielectric supporting means 9, adjacent the free end of wave guide or horn 12. A metallic cover 10, which acts as a reflector of electromagnetic waves, is placed ad-

adjacent material 8, on the side thereof opposite from guide 12.

The operation of this embodiment is exactly similar to that described in detail above with reference to Figs. 1-5 by utilizing substantially-circularly-polarized waves for the energy applied to the body to be heated; the incident waves pass through the material 8 at least twice before they can enter the rectangular wave guide 11—that is, the waves make at least two complete roundtrips through material 8 before they get back to the source. During these complete roundtrips, a large proportion of the energy content of the original wave is abstracted from it, so that a maximum heating of body 8 is accomplished, together with a reduction of the amplitude of the standing waves set up in the high-frequency feed line because of the reduction of amplitude of the wave reflected back into the source.

The operation of the modification of Figs. 6-8 is exactly similar in all respects to that of Figs. 1-4, except that in the modification of Figs. 6-8 a transition member is not used between the rectangular wave guide and the substantially square wave guide; both modifications are dielectric heating devices in which a linearly-polarized wave is converted to a circularly-polarized wave, so to one having a substantial degree of elliptical polarization, before being applied to the dielectric material, the wave after its conversion being passed through the material to heat the same, and said wave making at least two roundtrips through said material before said wave gets back to the feed line from the high-frequency source.

Although use of the apparatus for only the heating and defrosting of foods has been mentioned, it will be appreciated that the apparatus is applicable to other uses, for example to therapeutics.

Although the structures illustrated are preferably made from sheet copper, the inside surfaces of the devices may be silver-plated if desired, so that the losses may be reduced; silver loss is smaller than copper loss.

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 high-frequency heating system comprising, in combination, a hollow wave guide, a horn coupled to one end of said wave guide, means for providing at said one end of said wave guide a linearly-polarized high-frequency wave, said horn being constructed and arranged to convert said linearly-polarized wave into a wave having a substantial degree of elliptical polarization, a body of dielectric material coupled to the output end of said horn to receive said elliptically-polarized wave, and an electromagnetic-wave-reflecting surface on the side of said body opposite from said horn, whereby electromagnetic energy is reflected back through said body.

2. A high-frequency heating system comprising, in combination, a hollow wave guide, a horn coupled to one end of said wave guide, means for supplying a high-frequency wave to said wave guide, said horn being adapted to produce circular polarization of said wave, a body of dielectric material coupled to the output end of said horn to receive said circularly-polarized wave, and an electromagnetic-wave-reflecting surface on the

side of said body opposite from said horn, whereby electromagnetic energy is reflected back through said body.

3. A high-frequency heating system comprising, in combination, a hollow rectangular wave guide, a substantially square wave guide coupled to one end of said rectangular guide, the walls of said substantially square guide lying at an angle of substantially 45° to the respective walls of said rectangular guide and the center lines of said guides being collinear, means for supplying a high-frequency wave to said rectangular guide, a body of dielectric material coupled to the free end of said substantially square guide to receive wave energy therefrom, and an electromagnetic-wave-reflecting surface on the side of said body opposite from said substantially square guide, said reflecting surface being substantially perpendicular to the sides of said square guide.

4. A dielectric heating system comprising, in combination, a hollow rectangular waveguide, means for setting up a transverse electric mode wave of a predetermined energy content in said guide with the electric vector thereof extending at right angles to the longer side of said guide, the wavelength of said wave being such that said wave is incapable of propagation in said guide when the electric vector thereof extends at other than a right angle to said longer side, means for producing a substantial degree of elliptical polarization of said wave, a dielectric body to be heated coupled to said last-named means to receive said elliptically-polarized wave and to attenuate the same as it passes through said body, and means for reflecting the unattenuated energy of said wave back toward said waveguide.

5. A dielectric heating system comprising, in combination, a hollow rectangular waveguide, means for setting up a transverse electric mode wave of a predetermined energy content in said guide with the electric vector thereof extending at right angles to the longer side of said guide, the wavelength of said wave being such that said wave is incapable of propagation in said guide when the electric vector thereof extends at other than a right angle to said longer side, means for producing a substantial degree of elliptical polarization of said wave, a dielectric body to be heated coupled to said last-named means to receive said elliptically-polarized wave and to attenuate the same as it passes through said body, and means for reflecting the unattenuated energy of said wave back toward said waveguide, the electric vector of said reflected wave extending at other than a right angle to said longer side.

6. A dielectric heating system comprising, in combination, a hollow rectangular waveguide, means for setting up a transverse electric mode wave of a predetermined energy content in said guide with the electric vector thereof extending at right angles to the longer side of said guide, the wavelength of said wave being such that said wave is incapable of propagation in said guide when the electric vector thereof extends at other than a right angle to said longer side, means for producing a substantial degree of elliptical polarization of said wave, a dielectric body to be heated coupled to said last-named means to receive said elliptically-polarized wave and to attenuate the same as it passes through said body, and means for reflecting the unattenuated energy of said wave back toward said waveguide, the electric vector of said reflected wave extending at other than a right angle to said longer

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side so that it cannot enter said waveguide but is reflected therefrom back toward said body.

7. A dielectric heating system comprising, in combination, a hollow rectangular waveguide, means for setting up a transverse electric mode wave of a predetermined energy content in said guide with the electric vector thereof extending at right angles to the longer side of said guide, the wavelength of said wave being such that said wave is incapable of propagation in said guide when the electric vector thereof extends at other than a right angle to said longer side, means for producing a substantial degree of elliptical polarization of said wave, a dielectric body to be heated coupled to said last-named means to receive said elliptically-polarized wave and to attenuate the same as it passes through said body, and means for reflecting the unattenuated energy of said wave back toward said waveguide, the electric vector of said reflected wave extending at other than a right angle to said longer side so that it cannot enter said waveguide but is reflected therefrom back toward said body to again pass therethrough, said reflecting means acting to rereflect the remaining unattenuated energy of said wave back toward said guide, the electric vector of said rereflected wave after its second roundtrip passage through said body extending at substantially a right angle to said longer side.

8. A dielectric heating system comprising, in combination, a hollow rectangular waveguide, means for setting up a transverse electric mode wave of a predetermined energy content in said guide with the electric vector thereof extending at right angles to the longer side of said guide, the wavelength of said wave being such that said wave is incapable of propagation in said guide when the electric vector thereof extends at

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other than a right angle to said longer side, means for producing a substantial degree of elliptical polarization of said wave, a dielectric body to be heated coupled to said last-named means to receive said elliptically-polarized wave and to attenuate the same as it passes through said body, and means for reflecting the unattenuated energy of said wave back toward said waveguide, the electric vector of said reflected wave extending at other than a right angle to said longer side so that it cannot enter said waveguide but is reflected therefrom back toward said body to again pass therethrough, said reflecting means acting to rereflect the remaining unattenuated energy of said wave back toward said guide, the electric vector of said rereflected wave after its second roundtrip passage through said body extending at substantially a right angle to said longer side, substantially all of the energy content of said wave being absorbed by said body in the two roundtrip passages of said wave through said body, said energy serving to heat said body.

KARL J. STIEFEL.

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Certificate of Correction

Patent No. 2,480,682

August 30, 1949

KARL J. STIEFEL

It is hereby certified that errors appear in the printed specification of the above numbered patent requiring correction as follows:

Column 1, line 38, after the word "invention" strike out the period and insert instead a semicolon; column 5, line 31, strike out "rene, and from 30 to 45 per cent of acronitrile."; column 6, Equation 18a, for that portion reading

$$\left(\frac{\lambda_0}{2a}\right)^2 \quad \text{read} \quad \left(\frac{\lambda_0}{2a}\right)^2$$

and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 17th day of January, A. D. 1950.

[SEAL]

THOMAS F. MURPHY,
Assistant Commissioner of Patents.

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