United States Patent

Admiraal

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[54] **MICROWAVE DRYING APPARATUS AND METHOD**

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[52] **U.S. Cl.** **219/10.55,** 34/1

[51] **Int. Cl.** **H05b 9/06**

[58] **Field of Search** ....34/1, DIG. 19; 219/10.55

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Assistant Examiner—Hugh D. Jaeger

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[57] **ABSTRACT**

Apparatus and method for drying moisture-laden dielectric materials by microwave energy and including directing microwave energy from a generator to opposite sides of material to be dried. Means is provided for protecting the generator from microwave energy reflected by the material. It is preferable to include means for controlling the output of the generator in accordance with the moisture content of the portion of the material exposed to the microwave energy. This is accomplished by measuring energy transmitted through the material, and controlling the output of the generator inversely relative to the level of the transmitted energy.

18 Claims, 10 Drawing Figures

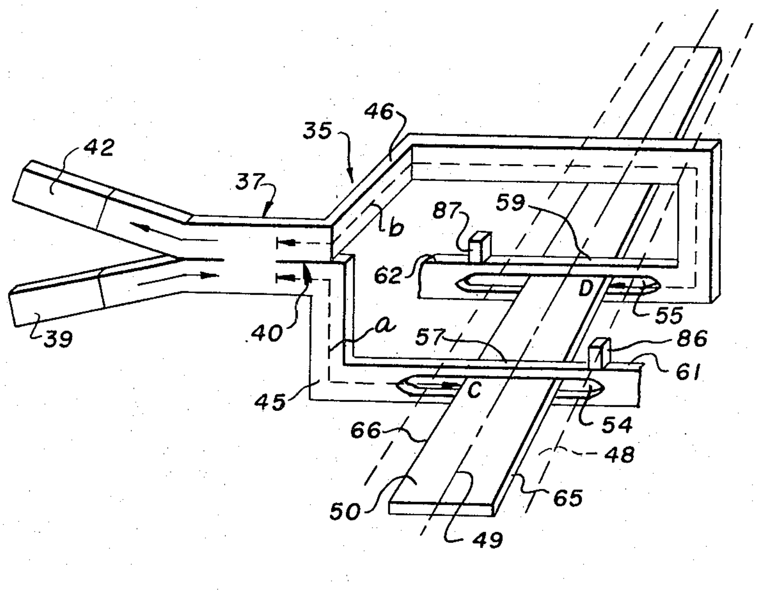

Fig. 1.

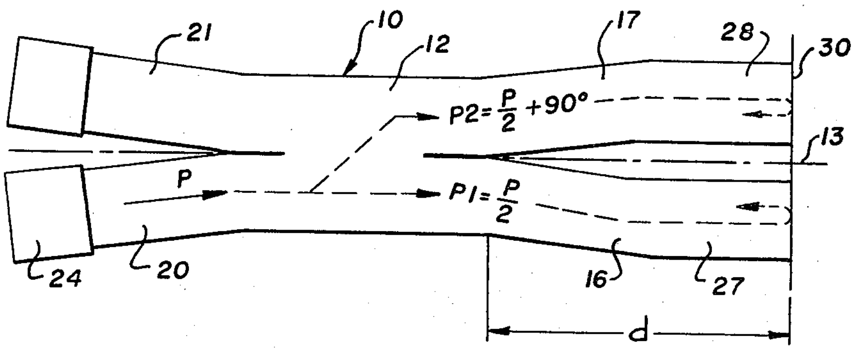

Fig. 2.

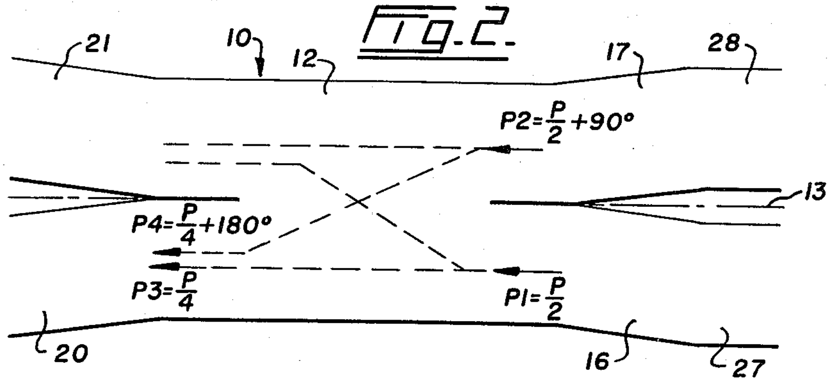

Fig. 3.

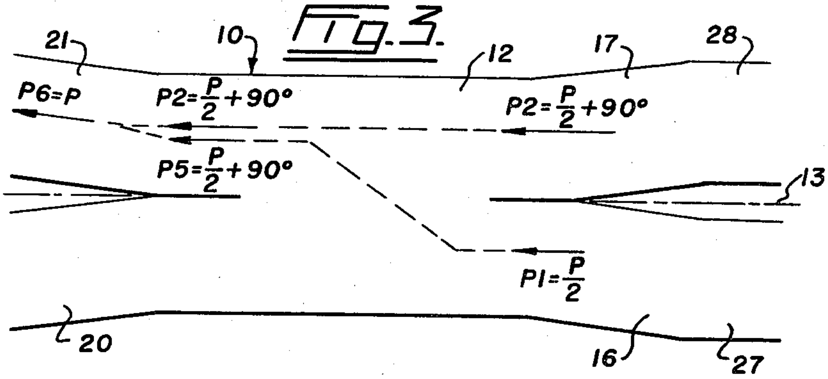

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Fig. 4.

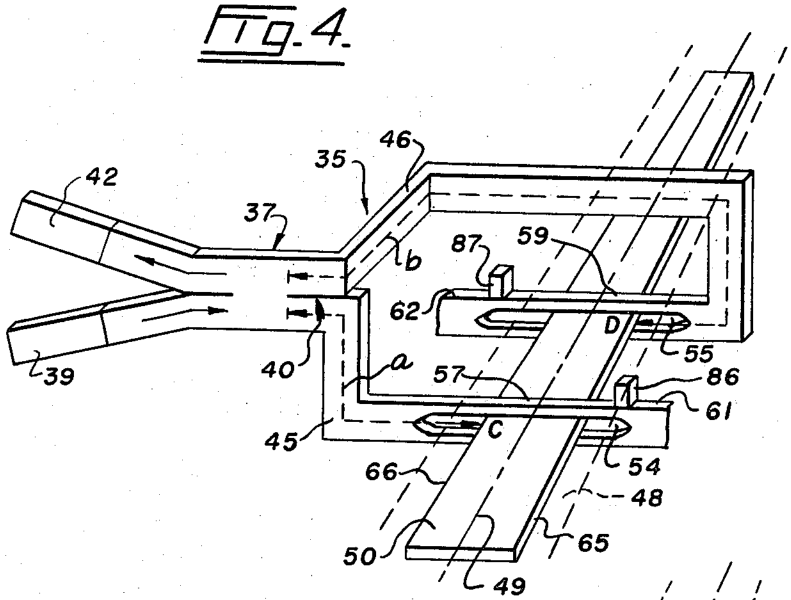
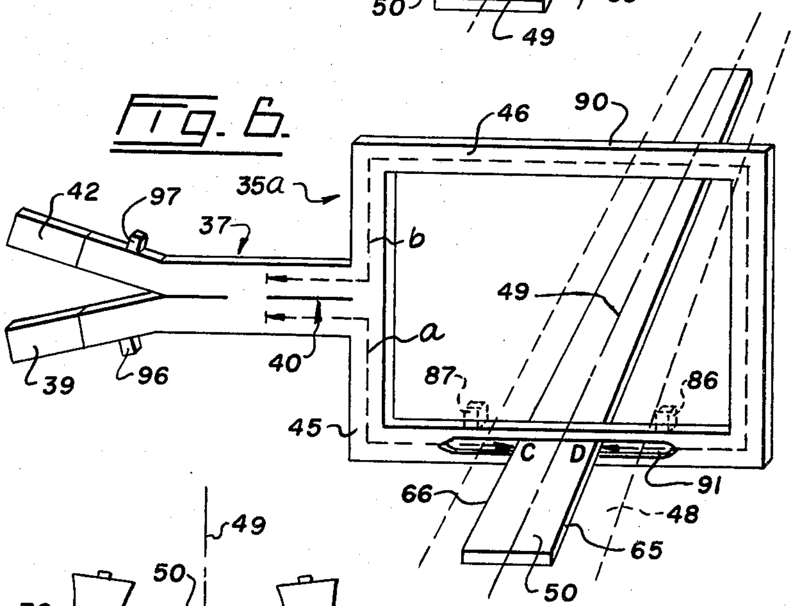


Fig. 6.



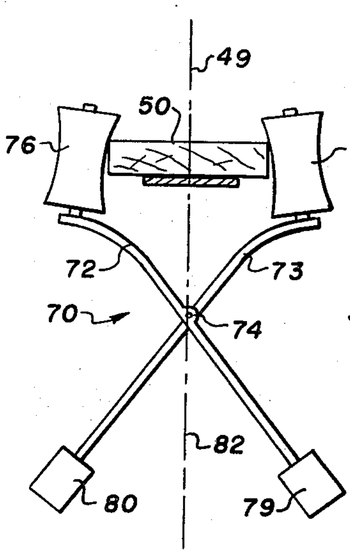


Fig. 5.

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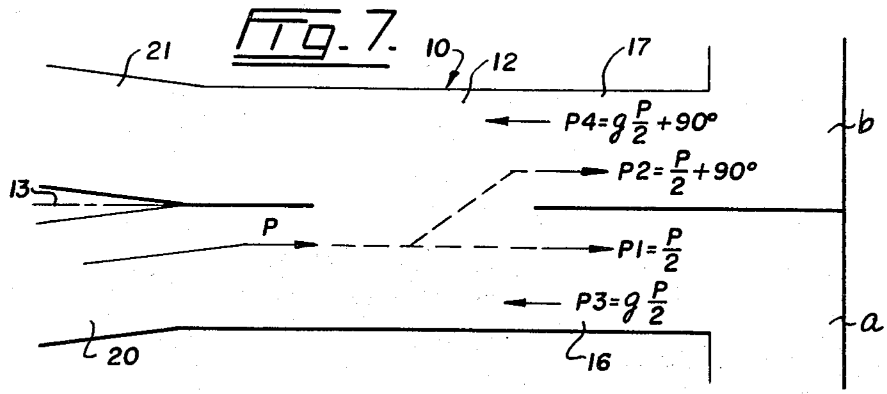

Fig. 7.

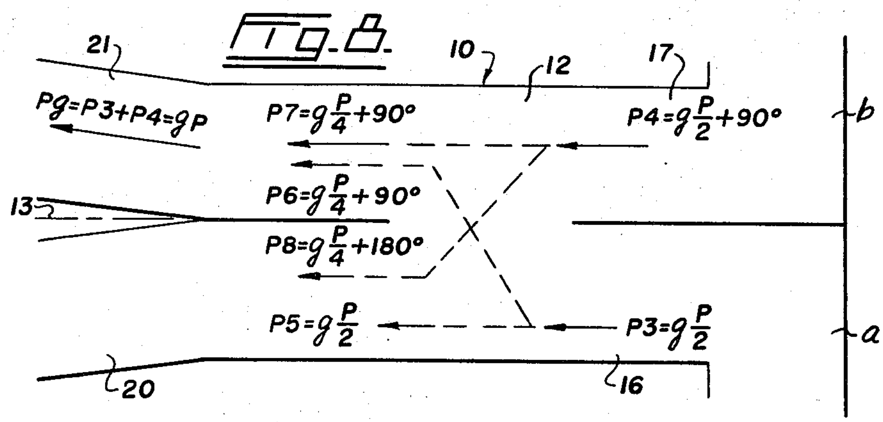

Fig. 8.

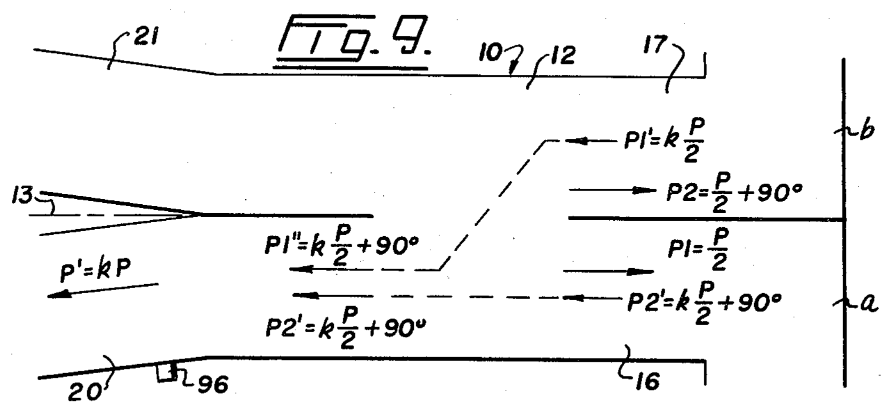

Fig. 9.

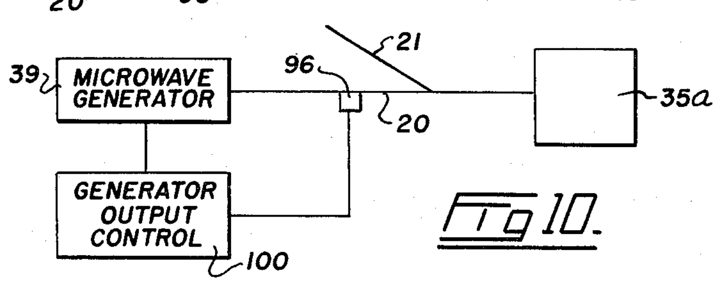

Fig 10.

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MICROWAVE DRYING APPARATUS AND METHOD

This invention relates to apparatus and methods for drying moisture-laden materials, such as lumber, wood based materials, bagasse, paper and the like by means of microwave energy.

Different types of materials can be dried by the present apparatus and methods, but for the sake of convenience the invention is described herein relative to the drying of lumber.

Heretofor the drying of lumber by means of microwave energy has been difficult and not practical in a commercial sense. The main difficulty is caused by the fact that the moisture content of lumber varies greatly from piece to piece and very often throughout the length of each piece. As the cost of microwave generating equipment and the amount of power consumed are very high, it has not been thought practical economically to dry by means of microwave energy. Another problem is caused by the fact that some microwave energy is reflected by the lumber back to the generator, and this causes serious problems.

The present invention greatly reduces these problems by directing microwave energy from a generator to opposite sides of the lumber, preferably in directly opposed areas. This means that the microwave generator "sees" portions of the board which have substantially the same moisture content. If the output of the generator is controlled in accordance with the moisture content of the lumber exposed to the microwave energy, this energy will increase and decrease in accordance with the moisture content. This is contemplated by the present invention, and includes means for measuring the microwave energy transmitted by the lumber and controlling the output of the generator inversely relative to the transmitted energy. The invention also includes a stopper or means for protecting the microwave generator from microwave energy reflected by the lumber.

The microwave drying method according to this invention comprises dividing microwave energy from a microwave generator into two equal parts, and directing said energy parts through two separated channels to opposite sides of the lumber to be dried, the distance of travel through one of said channels to the longitudinal centerline or to a side of the lumber being equal to the distance of travel through the other of said channels to said centerline or lumber side plus a whole number of half wavelengths of the microwaves from said generator. It is preferable according to this method to direct the two parts of the microwave energy to directly opposite areas of the lumber. The method also includes measuring the microwave energy transmitted through the lumber and controlling the output of the microwave generator inversely relative to the level of the transmitted microwave energy.

The microwave energy from the generator is preferably divided by a four-port hybrid which directs the energy to the two channels and, at the same time, protects the generator from microwave energy reflected by the lumber.

Apparatus according to the present invention comprises a microwave generator, means for dividing microwave energy from the generator into two equal parts, and separate channels for directing said two energy parts to opposite sides of lumber to be dried, the length of one of said channels to the longitudinal centerline or the side of the lumber being equal to the length of the other of said channels to the center line or lumber side plus a whole number of half wavelengths of the microwaves from said generator. These channels are preferably located to direct the two energy parts against directly opposite areas of the lumber. The apparatus also includes means for measuring the microwave energy transmitted through the lumber, and controlling means for regulating the output of the generator inversely relative to the level of the transmitted energy.

In the preferred form of the apparatus, a waveguide system having two channels is used, and the channels of this waveguide system are coupled to the generator by a four-port hybrid. In the preferred form of the invention, the two waveguide channels are in the form of a closed loop or ring, and the lumber travels through a slot in the loop or ring. Guide means is provided for maintaining the longitudinal center line of the lumber on an electromagnet center line. The length of one of the channels to this electromagnetic center line is equal to the length of the other of the channels plus a whole number of half wavelengths of the microwaves from the generator. With this arrangement, the microwave energy transmitted through the lumber travels back through the channels towards the hybrid. This transmitted energy is measured and the output of the generator is controlled inversely relative to the transmitted energy.

It has been found that the transmitted energy levels are mainly related to the moisture content of the transmitting lumber. As the amount of moisture in the lumber increases so increases the amount of microwave energy absorbed in the drying process and vice versa. The transmitted power represents the amount of power or energy which the lumber was unable to absorb. In this way, lumber of high moisture content and therefore very low in transmitting power, receives automatically maximum microwave energy, while lumber of lower moisture content receives less energy. This ensures maximum power being applied to wet areas without applying too much power to dryer areas, even though these areas are in the same piece of lumber or in adjacent different pieces.

The method and apparatus of the present invention will be understood from the following description in connection with the accompanying drawings, in which

FIGS. 1, 2 and 3 diagrammatically illustrate the operation of a four-port hybrid,

FIG. 4 illustrates one form of microwave drying apparatus in accordance with this invention,

FIG. 5 illustrates an example of guide means for lumber being dried in this apparatus,

FIG. 6 illustrates a preferred form of microwave drying apparatus according to this invention,

FIGS. 7, 8 and 9 illustrate the operation of the four-port hybrid when used in the drying apparatus of FIG. 4 or FIG. 6, and

FIG. 10 illustrates a control system for the drying apparatus.

When a microwave generator is directly coupled to a slotted waveguide through which lumber travels to be dried, all microwave power or energy reflected from the lumber face returns to the generator. This endangers the generator and interferes with its proper operation. This situation is avoided by the use of a four-port hybrid between the generator and the slotted waveguide.

FIG. 1 illustrates the basic working of a four-port hybrid **10**. This hybrid is formed with a central section **12** and has a longitudinal center line **13**. A first pair of arms **16** and **17** project from one end of the central section on opposite sides of center line **13** at an angle to each other, and a second pair of arms **20** and **21** project from the opposite end of the central section of the hybrid on opposite sides of said center line and at an angle to each other. These arms constitute the four ports of the hybrid. A microwave generator **24** is coupled to arm **20**, and arm **21** is connected to suitable microwave energy absorbing means, such as a waterload or another system utilizing microwave energy. Channels **27** and **28** are connected to arms **16** and **17**, respectively, and for the purpose of this illustration, a reflector plate **30** extends across the two channels **27** and **28**.

When microwave energy or power P comes from generator **24** into port **20** then P1 equalling P/2 continues through port **16**, and P2 equalling P/2 will cross the center line **13** and continue through port **17**. The crossing of the center line gives an automatic 90° phase shift to P2. If P1 and P2 both travel the same distance *d* before being reflected by reflector **30**, their phase relationship does not change by the time they re-enter ports **16** and **17**.

The powers P1 and P2 in FIG. **2** represent their returning or reflected powers, and each one has the tendency to split again into two equal parts, each one of them being equal to P/4. If P3 is that half of P1 which does not cross over the center line, and P4 is that half of P2 which does cross over the center line and therefore has a further 90° phase shift, then there are in port **20** two electromagnetic waves of equal power but with a phase shift of 180° or half a wavelength. These two waves cancel each other completely and therefore prohibit propagation in port **20**, thereby protecting the microwave generator.

FIG. **3** illustrates the results of the above-mentioned cancellation. Since no power from ports **16** and **17** can enter port **20**, and since it has to go somewhere, the only way open is port **21**, that is, **P2** does not cross over the centerline therefore maintains its 90° phase shift while **P5** has crossed over the center line and therefore has a 90° phase shift. There are now in port **21** two electromagnetic waves of equal power and of identical phase and therefore they reinforce each other and travel as one wave of power **P6** which equals P through port **21** towards the absorption means.

If the total reflection surface **30** is replaced by a surface with a partial reflection coefficient of g, such as the surface of moist lumber, then the same reasoning holds as above, the only difference being in the various power levels, for example, **P6** equalling $g \times$ P.

FIG. **4** illustrates one form of microwave drying apparatus **35** in accordance with this invention. This apparatus includes a four-port hybrid **37** similar to hybrid **10** described above, and which couples a microwave generator **39** to a waveguide system **40**. Suitable microwave absorption means, such as a waterload **42**, is coupled to the hybrid.

Waveguide system **40** has a pair of arms or channels **45** and **46** which extend to opposite sides of a path **48** having an electromagnetic center line **49** and along which lumber **50** travels with its longitudinal center line coinciding with centerline **49**. Channels **45** and **46** of the waveguide have slots **54** and **55** therein through which path **48** extends. As far as this invention is concerned, the effective parts of channels **45** and **46** terminate in ends **57** and **59** substantially at center line **49**. However, the channels **45** and **46** may continue on beyond the lumber path in section **61** and **62** so that microwave energy transmitted through the lumber may be used for any desired purpose.

If the path lengths of FIG. **4** indicated by a and b are not both equal to d of FIG. **1**, the distance from the hybrid to a reflecting surface, but is

$a = d$, and $b = d + m\,\lambda/2$ where m is an integer and λ is the wavelength of the microwaves, then the above reasoning still holds because the distance

$b - a = m\,\lambda/2$ is being traveled twice, therefore a phase shift of

$2 \times m\,\lambda/2 = m\,\lambda$ takes place so that no extra phase shift has been introduced.

If the condition $b - a = m\,\lambda/2$ is realized for a board of width w then the center line of that board coincides with the electromagnetic center line (EMCL) **49**. If now a board of any other width is placed with its center line on the EMCL, then the pathlengths of a and b are changed into a^1 and b^1 respectively but in identical ways therefore the term $b^1 - a^1 = m\,\lambda/2$ still holds.

Summarizing, it can be said that independent of power level P, reflection coefficient g or lumber width w, the microwave generator will receive no reflected power if all boards are centered on the EMCL. As an example, with a frequency of 915 MHz, a wavelength results in the guide system of 17.2 inches, there is an EMCL every 4.3 inches (or $\lambda/4$) across the width of the waveguide slot. Therefore within approximately 2 inches of the physical center line of the system there is an EMCL.

In order the comply with this reasoning, the effective length of channel **46** to the edge **65** of lumber **50** or center line **49** equals the effective length of channel **45** to edge **66** of the lumber or center line **49** plus a whole number of half wavelengths of the microwaves from generator **39**.

It is clear that when drying lumber of varying widths in apparatus **35**, it is not possible to use a one-sided guide rail, and therefore, it is necessary to provide means for keeping the longitudinal center lines of the lumber on the electromagnetic center line **49**. FIG. **5** illustrates one way of accomplishing this. A scissor type guide **70** can be used for this purpose. Guide **70** includes a pair of arms **72** and **73** pivotally connected at **74** to each other said arms carrying rollers **76** and **77** at upper ends thereof equally spaced from pivot **74**, and weights **79** and **80** at lower ends thereof, also equally spaced from the pivot. Guide **70** has a vertical center line **82** which extends through pivot **74** and coincides with the electromagnetic center line **49** of apparatus **35**.

Lumber **50** to be dried by this apparatus is directed between rollers **76** and **77** which apply substantially equal pressure to opposite edges of the lumber and so positions the longitudinal centerline thereof on the electromagnetic center line.

As stated above, a certain percentage of the microwave energy directed against the opposite edges of the lumber is transmitted theretrough, and the amount transmitted depends upon the moisture content of the lumber. As the moisture content of the lumber is constantly changing, it is desirable to control the power from the microwave generator in accordance with the changed moisture contents. This can be accomplished by positioning detectors **86** and **87** on the outer end sections **61** and **62** of waveguide channels **45** and **46**, respectively. These detectors also known as directional power meters are well known and do not need description herein. These detectors are connected to a controller for the microwave generator **39** in the manner described hereinafter.

FIG. **6** illustrates a preferred form of drying apparatus **35a** in accordance with this invention. In this example, the arms or channels **45** and **46** of waveguide system **40** are formed in a closed loop **90** having a single slot **91** therein through which path **48** extends. The same relationship as above exists between the effective lengths of channels **45** and **46** to the edges **66** and **65** of lumber **50** or to the electromagnetic center line **49**. If in this case, the detector **86** for channel **45** were located in arm **46** and the detector **87** for channel **46** were located in arm **45**, as indicated in broken line in FIG. **6**, then there would be completed the transformation of FIG. **4** to FIG. **6** by squeezing all waveguide system components into one plane. However, if this were done a difficulty arises because the detector **86** not only measures that part of the power flowing through arm **45** that is transmitted through the lumber from C to D and beyond but also that part of the power flowing through arm **46** that is reflected at the lumber face D. Therefore the detectors **86** and **87** have been replaced by a single detector **96** in arm **20** which detector will measure, as will be shown later, the sum of the two transmitted powers flowing back to generator **39**. For convenience another detector **97** can be added in arm **21** for the measurement of the reflected power flowing to waterload **42**.

As stated above, all of the reflected microwave power or energy is directed back to waterload **42** and so the microwave generator **39** is protected against this. In actual practice, this happens only if the areas C and D of the lumber have the same reflection coefficient. Since C and D in FIG. **4** are spaced apart, the generator is protected only if the moisture content of the boards to be dried is relatively constant. If the moisture content in different areas of a given board or if the moisture content of successive boards is different, the reflection coefficient in apparatus **35** will be different, and the microwave generator can be exposed to reflected power. However, apparatus **35** can be used for lumber in which the moisture content does not vary greatly within boards or successive boards.

Apparatus **35a** eliminates this problem since C and D are directly opposite each other or, in other words, the microwave generator "sees" substantially the same portion of each board.

When the energy or power transmitted through the lumber is used to control the output of the generator, the same problem arises with apparatus **35** since the power transmitted in channel **45** may be different from that transmitted in channel **46** at any given instance. Apparatus **35a** also eliminates this problem.

The loop or ring waveguide system of apparatus **35a** in FIG. **6** is considered to be much better than apparatus **35** for general purposes. If, in apparatus **35a**, the path lengths a and b fulfill the following condition:

$$b = a + m\,\lambda/2 \qquad (1)$$

where λ is the MW wavelength in the waveguide and m is an integer, then all reflected power from the lumber faces C and D will flow to the waterload and all transmitted power exiting from the lumber faces D and C will flow to the generator.

FIG. 7 shows how the energy P flowing from the generator through port **20** is split into two equal parts P1 and P2, but P2 also obtained a 90° phase shift because it crossed the center line of the four-port hybrid. After travelling through the respective waveguides *a* and *b*, part of the energy is reflected back. Since both P1 and P2 "see" the same portion of the lumber (albeit from two different sides) the same part *g* of P1 and P2 is reflected back as P3 and P4, respectively. Since both arms *a* and *b* have been travelled twice by the time the four-port hybrid is reached, any additional phase shift due to $b \neq a$ amounts to a whole number of full wavelengths therefore has no influence. The only phase shift between P3 and P4 is that P4 is still 90° ahead of P3 (as was the case between P2 and P1).

In FIG. **8** illustrates what happens when P3 and P4 enter the four-port hybrid and try to split into two equal parts. In port **20** you then have P5 (or half of P3) and P8 (or the crossed over half of P4 which gets another 90° phase shift for crossing). These are now two electromagnetic wave systems of equal magnitude but with a 180° phase shift between them, therefore cancellation between the two wave systems will take place, thus prohibiting propagation towards the generator. In port **21** the two wave systems P6 and P7 from ports **16** and **17** are of the same magnitude and phase when they meet, therefore, they will reinforce each other and flow to the water load.

Since P5 and P8 have to go somewhere, they will act and reinforce each other in a manner identical to P6 and P7, respectively, and will also flow through port **21** to the water load. Therefore the amount of reflected power ending up in the water load is $P9 = P3 + P4 = gP$ or the total amount of the original P which has been reflected by the lumber.

As far as the transmitted power is concerned, there is a completely different result. In FIG. **9** P results in P1 flowing through arm *a* and P2 flowing through arm *b* (P2 has already a 90° phase shift). Those equal parts of P1 and P2 that are not reflected at the lumber faces C and D will enter the lumber where a certain fraction will be absorbed (the fraction depending on the lumber portion CD in the wave guide) and the remainder P1′ and P2′ will continue on their way through the wave guides b respectively a. If the transmission coefficient for the portion CD of the lumber is h and $(1-g)\,h = k$ then you have:

$P \rightarrow P1 = (P/2)$ through arm $a \rightarrow P1' = k\,P/2$ through arm b

and

$P \rightarrow P2 = (P/2) + 90°$ through arm $b \rightarrow P2' = k\,(P/2) + 90°$ through arm a

In FIG. **9** you find now (through an identical exercise as in FIG. **8**) that the only way the transmitted power $P2'$ and $P1'$ can go is through port **20** towards the generator since port **21** is a prohibited area due to cancellation.

Since the transmitted power P′ represents the amount of power which the lumber was unable to absorb and therefore is going to waste (in the generator) it should be kept to a tolerable minimum Δ P, depending on the wood properties. Therefore P′ should be measured with detector **96** and used to control the output of the generator so that $P' \leq \Delta P$. In this way lumber of high moisture content and therefore very low in transmitted power, receives automatically maximum power while lumber of lower moisture content gradually receives less power, thus resulting in a slowdown of the drying process when the lumber reaches its desired final moisture content.

FIG. **10** diagrammatically illustrates a system for controlling the power output of microwave generator **39** in accordance with the moisture content of the lumber being subjected to the drying action of microwaves at any given instant. The detector or measurer **96** of transmitted microwave energy P′ is operatively connected to an output control unit **100** for generator **39**. The arrangement is such that as the moisture content of the wood being "viewed" increases, the transmitted energy decreases and the output of the generator is increased, and vice versa.

I claim:

1. Microwave drying apparatus for moisture-laden dielectric material comprising a microwave generator, means for dividing microwave energy from the generator into two equal parts, and separate channels for directing said two energy parts to opposite sides of material to be dried, the length of one of said channels to the longitudinal center line of the material being equal to the length of the other of said channels plus a whole number of half wavelengths of the microwaves from said generator.

2. Microwave drying apparatus as claimed in claim **1** in which said channels are located to direct said two energy parts against directly opposite areas on said material.

3. Microwave drying apparatus as claimed in claim **1** including means for detecting the microwave energy that is transmitted through said material, and controlling means for regulating the output of the microwave generator inversely relative to the level of the transmitted energy.

4. Microwave drying apparatus for moisture-laden dielectric material comprising a waveguide having two channels extending to outer ends on opposite sides of a path along which material to be dried travels, said path having an electromagnetic center line and said material being guided to travel with its center line on said electromagnetic center line and between said two channel ends, a microwave generator, a four-port hybrid coupling the waveguide channels to the generator, the length of one of said channels to the electromagnetic center line being equal to the length of the other of said channels plus a whole number of half wavelengths of the microwaves from said generator, said waveguide channels directing microwave energy from the generator to opposite sides of material moving along said path.

5. Microwave drying apparatus as claimed in claim **4** in which said two channel ends are located close to each other.

6. Microwave drying apparatus as claimed in claim **4** in which said channel ends are located directly opposite from each other.

7. Microwave drying apparatus as claimed in claim **4** including control means operated by microwave energy transmitted through said material to control the output of the microwave generator inversely relative to the level of the transmitted energy.

8. Microwave drying apparatus as claimed in claim **4** in which said channel ends are located directly opposite from each other whereby microwave energy transmitted through said material travels back through said channels, and control means operated by said transmitted energy to control the output of the microwave generator inversely relative to the level of the transmitted energy.

9. Microwave drying apparatus as claimed in claim **4** including microwave energy absorption means coupled to one of the ports of said hybrid.

10. Microwave drying apparatus for moisture-laden dielectric material comprising a hybrid having a common central section and a longitudinal center line, a first pair of arms projecting from one end of the central section on opposite sides of the center line, a second pair of arms projecting from an opposite end of the central section on opposite sides of the hybrid center line, a microwave generator coupled to one arm of said second pair of arms so that microwave energy therefrom is directed through both of the arms of the first pair, a waveguide having two channels, one connected to each arm of said first pair, said two channels extending to outer ends on opposite sides of a path along which said material travels, said path having an electromagnetic center line and said material being guided to travel with its center line on said electromagnetic center line and between said two channel ends, the length of one of said channels to the electromagnetic center line being equal to the length of the other of said channels plus a whole number of half wavelengths of the microwaves from said generator, said waveguide channels directing microwave energy from the generator to opposite sides of the material moving along said path.

11. Microwave drying apparatus as claimed in claim **10** in which said two channel ends are located close to each other.

12. Microwave drying apparatus as claimed in claim **10** in which said channel ends are located directly opposite from each other.

13. Microwave drying apparatus as claimed in claim **10** including control means operated by microwave energy transmitted through the said material to control the output of the microwave generator inversely relative to the level of the transmitted energy.

14. Microwave drying apparatus as claimed in claim **10** in which said channel ends are located directly opposite from each other whereby microwave energy transmitted through said material travels back through said channels, and control means operated by said transmitted energy to control the output of the microwave generator inversely relative to the level of the transmitted energy.

15. Microwave drying apparatus as claimed in claim **10** including microwave energy absorption means coupled to the other of said second pair of arms.

16. The microwave drying method which comprises dividing microwave energy from a microwave generator into two equal parts, and directing said energy parts through two separate channels to opposite sides of material to be dried, the distance of travel through one of said channels to the longitudinal center line of the material being equal to the distance of travel through the other of said channels to said center line plus a whole number of half wavelengths of the microwaves from said generator.

17. The method according to claim **16** in which said two microwave energy parts are directed by the channels to directly opposite areas on said material.

18. The method according to claim **16** including detecting the microwave energy transmitted through said material, and controlling the output of the microwave generator inversely relative to the level of the transmitted microwave energy.

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