

[54] MICROWAVE HEATING APPARATUS WITH TUNING MEANS

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[51] Int. Cl. H05b 9/06

[58] Field of Search 219/10.55

[56] References Cited

UNITED STATES PATENTS

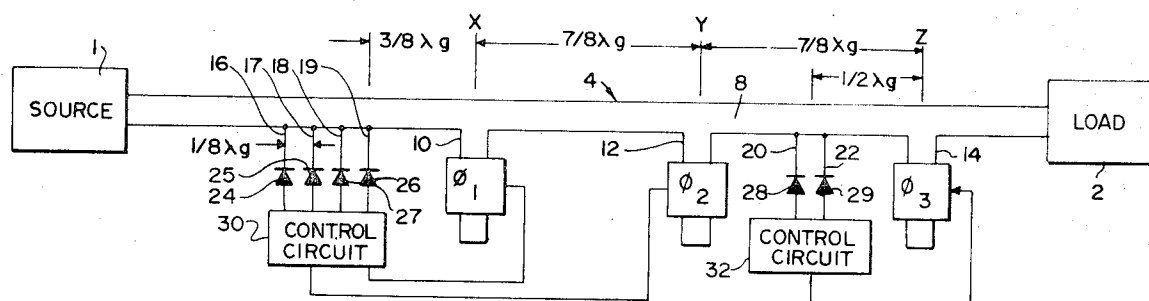
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[57] ABSTRACT

In a microwave heating apparatus the tuning means, connecting the microwave source to the microwave heating means in which a material is heated by exposure to microwave energy, comprises a main section of waveguide having first, second and a third branch waveguides each having an adjustable tuning stub in the form of a rotatable vane in a circular extension of each branch waveguide. A group of four sensing probes attached to the main section of waveguide between the source and first branch adjusts the effective electrical lengths of the tuning stubs in the first and second branch waveguides, and a further two sensing probes between the second and third branch waveguides adjust the effective electrical length of the tuning stub in the third branch waveguide.

2 Claims, 8 Drawing Figures



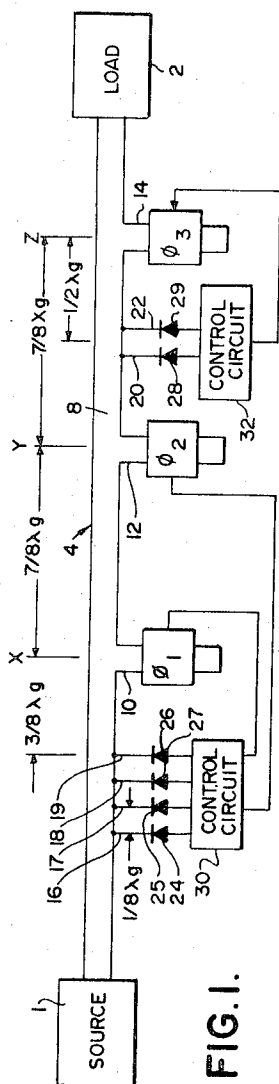


FIG. 1.

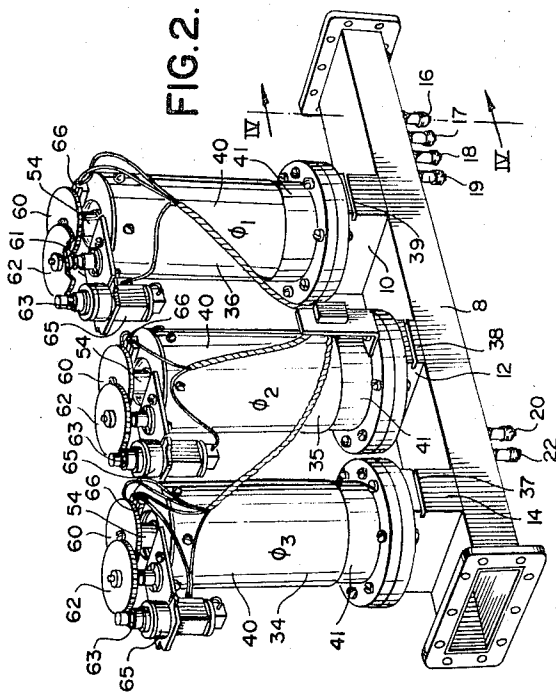


FIG. 2.

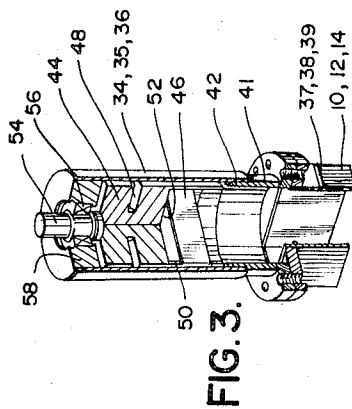


FIG. 3.

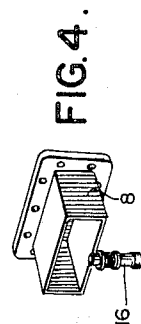


FIG. 4.

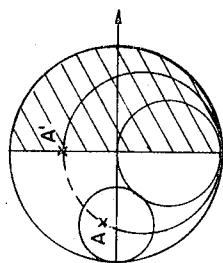


FIG. 5

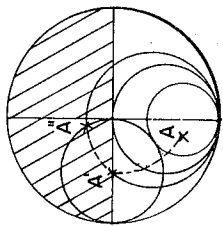


FIG. 6

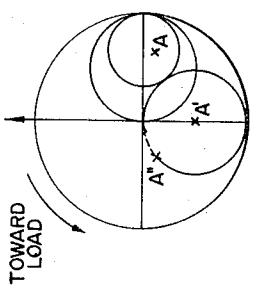


FIG. 7

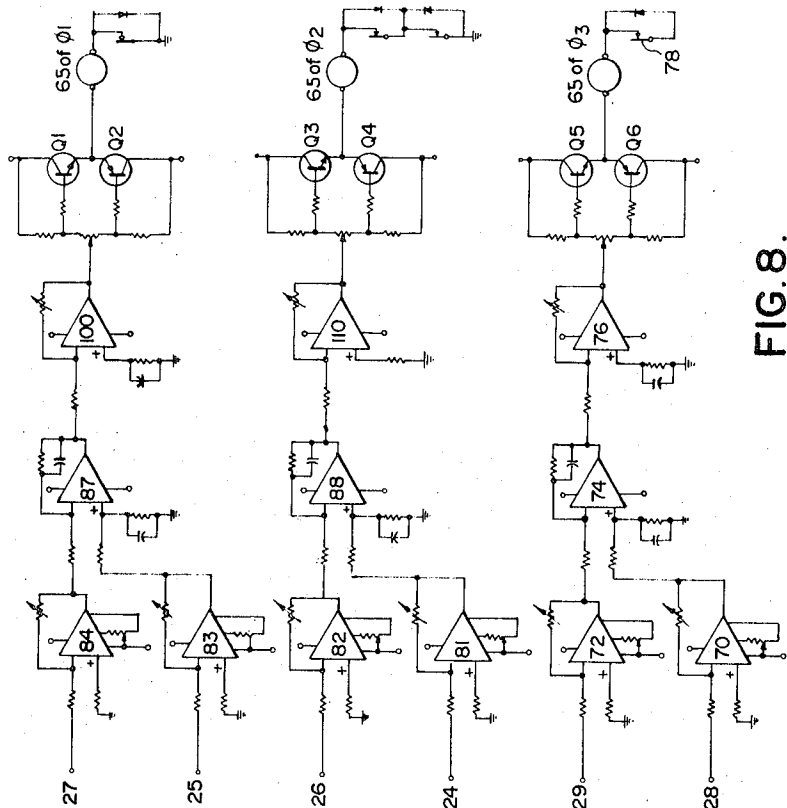


FIG. 8

MICROWAVE HEATING APPARATUS WITH TUNING MEANS

This invention relates to microwave heating apparatus, and is particularly concerned with tuning means for microwave heating apparatus.

Tuned or resonant microwave heating systems often offer a convenient means to efficiently couple a microwave energy source to heat, for example, continuous thin webs and filamentary materials. Some classes of known resonant microwave heating systems require some manually adjustable tuning mechanism to compensate for detuning of the system as a result of, for example, variations in the properties of the material being treated or changes in its transport speed at the heating position.

Although many known resonant microwave heating systems maintain proper tuning for extended periods of time during operation, nevertheless manual adjustment of the tuner by the operator is often required during starting up procedures and, as previously stated, is occasionally necessary during operation. When, however, the microwave heating system is detuned, full microwave power transfer to the material to be heated is not achieved and so incomplete heating results. Consequently, for most consistent product quality and operational convenience it would be desirable to provide in a microwave heating apparatus an automatically adjusted tuning means for tuning the apparatus.

It is an object of the present invention to provide, in a microwave heating apparatus, tuning means which will automatically tune the apparatus.

According to the present invention there is provided microwave heating apparatus, comprising a microwave energy source, and a microwave heating means, a microwave tuning means connecting the microwave energy source to the microwave heating means, the tuning means comprising a main waveguide section connecting the output of the microwave energy source to the input of the microwave heating means, first, second and a third branch waveguides connected to the main waveguide section at spaced positions therealong from the microwave energy source, first, second and third adjustable tuning stubs are attached to the first, second and third branch waveguides respectively, four signal sensing probes attached to the main waveguide section at spaced position therealong between the microwave energy source and the first branch waveguide, two further sensing probes attached to the main waveguide section at spaced positions therealong between the second and third branch waveguides, four microwave detectors each connected to one of said four sensing probes, two microwave detectors each connected to one of said two further sensing probes, a control circuit connected to said four microwave detectors and to said first and second adjustable tuning stubs to adjust, in response to said four microwave detector outputs, the effective electrical lengths of said first and second adjustable tuning stubs, and a control circuit connected to said two microwave detectors and to said third tuning stub to adjust, in response to the outputs of said two microwave detectors, the effective electrical length of the third tuning stub, whereby the microwave tuning means, in combination with the microwave heating means, presents a substantially non-reflecting microwave load to the microwave energy source.

In the accompanying drawings which illustrate, by way of example, an embodiment of the present invention,

FIG. 1 is a block circuit diagram of a microwave heating apparatus,

FIG. 2 is a corner view of a microwave tuning means in FIG. 1,

FIG. 3 is a partly sectioned corner view of a tuning stub shown in FIG. 2,

FIG. 4 is a sectional corner view along IV—IV, FIG. 2,

FIGS. 5 to 7 are impedance diagrams, and are shown beneath FIG. 2, and

FIG. 8 is a circuit diagram of a control circuit for the apparatus shown in FIG. 1.

Referring now to FIG. 1 there is shown a known microwave energy source 1, a microwave heating means 2, and a known microwave tuning means.

The microwave tuning means 4 includes a main waveguide section 8 connected to the microwave energy source 1 and microwave heating means 2 for heating a material by exposure to microwave energy from the microwave source. First, second and third branch waveguides 10, 12 and 14 are connected to the main waveguide section 8 at spaced positions therealong from the microwave energy source 1. First, second and third adjustable tuning stubs or variable short circuits ϕ_1 , ϕ_2 , and ϕ_3 respectively are attached to the first, second and third branch waveguides 10, 12 and 14 respectively. Four signal sensing probes 16 to 19 are attached to the main waveguide section 8 at spaced positions therealong between the microwave energy source 1 and the first branch waveguide 10. Two further sensing probes 20 and 22 are attached to the main waveguide section 8 at spaced positions therealong between the second and third branch waveguides. Four microwave detectors 24 to 27 are connected to the four sensing probes 16 to 19 respectively. Two microwave detectors 28 and 29 are connected to the two further sensing probes 20 and 22 respectively. A control circuit 30 is connected to the four microwave detectors 24 to 27 and to the first and second adjustable tuning stub ϕ_1 , and ϕ_2 to adjust, in response to the outputs of the four microwave detectors 24 to 27, the effective electrical lengths of the first and second adjustable tuning stubs ϕ_1 and ϕ_2 . A control circuit 32 is connected to the two microwave detectors 28 and 29 and the third tuning stub ϕ_3 to adjust, in response to the outputs of the two microwave detectors 28 and 29 the effective electrical length of the third tuning stub ϕ_3 .

As will be described later, the adjustments of the first, second and third tuning stubs ϕ_1 , ϕ_2 and ϕ_3 respectively in this manner causes the microwave tuning means 4, in combination with the microwave heating means 2, to present a substantially non-reflecting microwave load to the microwave energy source 1.

Referring to FIGS. 2 to 4, where similar parts to those shown in FIG. 1 are designated by the same reference numerals, the first, second and third tuning stubs ϕ_1 , ϕ_2 and ϕ_3 respectively, each have a circular cross-section waveguide 34 to 36 respectively, forming a butt joint with the first, second and third branch waveguides 10, 12 and 14 respectively. The first, second and third branch waveguides 10, 12 and 14 are rectangular in cross-section and the resulting discontinuity presented to microwave energy between them and the circular cross-section waveguides 34 to 36 is partially matched

by symmetrical inductive irises 37 to 39 respectively. The circular waveguides 34 to 36 are identical and each comprise two tubular sections 41 and 40 which, as shown in FIG. 3, are joined by a lap joint 42.

Also shown in FIG. 3 each tubular section 40 contains a metal block 44 of circular cross-section, rotatably mounted coaxially therein, with a diametrically disposed, short circuiting fin 46 secured to the end thereof. Each metal block 44 has an annular slot 48 which forms a radial waveguide. Each fin 46 is mounted in a tubular extension 50 of the metal block 44 and is spaced from the end surface 52 thereof, which forms a second microwave short circuit. As stated above the metal blocks 44 are rotatably mounted each by spindle 54 and bearing 56 in an end wall 58 of the tubular section 40.

Referring again to FIG. 2, each spindle 54 is coupled by reduction gears 60 to 63 to an electric motor 65. Each tubular section 40 has 2 switches 66 thereon for disconnecting the electric motor 65, limiting the rotation of the tuning stubs.

The sensing probes 16 to 19, 20 and 22 are identical and as shown in FIG. 4 extend through the wall of the main waveguide section 8.

The choice of separation of the tuning stubs ϕ_1 , ϕ_2 , and ϕ_3 is somewhat arbitrary but for reasons of mechanical convenience and ease of automation of the system, $7/8 \lambda_g$ (λ_g is the guide wavelength of the microwave energy) is chosen.

In operation, reference planes X, Y and Z are defined to be coincident with the equivalent planes of introduction of series reactance by tuning stubs ϕ_1 , ϕ_2 and ϕ_3 . With the source 1 propagating microwave energy along the main waveguide section 8 the microwave heating means, it is assumed that the load viewed from reference plane Z has an impedance denoted A on the impedance diagram shown in FIG. 5. It is also assumed that tuning stub ϕ_3 is capable of introducing a series reactance variable from $j0$ to $j\infty$. The fin 46 of tuning stub ϕ_1 is rotated by its motor 65 to introduce positive reactance until the input impedance viewed from reference plane Z is resistive and thus tuning stub ϕ_3 transforms the load impedance A (FIG. 5) to the new point A' through movement along a constant resistance circle. If the initial load impedance A has a positive reactance component (i.e., lies in the shaded area on the right hand side of FIG. 5), tuning stub ϕ_3 contributes $j0$. The load impedance viewed from reference plane Z with tuning stub ϕ_3 properly adjusted thus lies on the vertical axis if the load has a negative reactance component and lies in the shaded region of the impedance diagram shown in FIG. 5, if the load has a positive reactance component.

Viewed from reference plane Y, a plane $7/8 \lambda_g$ toward the source from reference plane Z, the combination of the load and the reactance introduced by tuning stub ϕ_3 insures that the impedance lies in the shaded upper half of the impedance diagram in FIG. 6. Referred to plane Y adjustment of tuning stub ϕ_3 transforms the load from point A to A' of FIG. 6. To achieve a matched load, tuning stub ϕ_2 must add positive reactance to transform the point A' to the point A'' via a constant resistance circle. Point A'' lies on the unit resistance circle when viewed from reference plane X and thus the load can be matched by adding appropriate positive reactance with tuning stub ϕ_1 .

The system is capable of matching an arbitrary load if tuning stub ϕ_3 is capable of introducing a reactance variable from $j0$ to $j\infty$, tuning stub ϕ_2 contributes $+j1$ to $-j2$ and tuning stub ϕ_1 is variable from $j0$ to $j\infty$. Consequently the equivalent position of the short circuits in the tuning stubs need only be variable by $0.25\lambda_g$, $0.3\lambda_g$, and $0.25\lambda_g$ for tuning stubs ϕ_1 , ϕ_2 and ϕ_3 respectively. This feature allows use of a variable short circuit with limited reactance range to form the tuning stubs.

Automation of the tuning system described above will now be described with reference to FIG. 2 to 8. The basic elements of the system are shown in FIG. 2. Tuning stub ϕ_3 is required to introduce a positive reactance to cancel the load reactance when it is negative or to introduce no reactance when the load reactance is positive. This function is automated by sensing the quadrature component of reflection coefficient referred to reference plane Z by subtracting the voltage outputs of the two detectors 28 and 29.

This is accomplished by the voltages of different magnitudes from the detectors 28 and 29 being passed to amplifiers 70 and 72 respectively. The amplified signals from the amplifiers 70 and 72 are fed to difference amplifier 74. The output signal from difference amplifier 74 is amplified by amplifier 76, an inverting amplifier with adjustable gain, whose output signal is passed to transistors Q5 and Q6 which prevent excessive loading of the amplifier 76. The signals from transistors Q5 and Q6, which function as emitter followers, provide an output control signal of low impedance for the electric motor 65 of tuning stub ϕ_3 .

Thus a signal proportional to the horizontal component of impedance coordinates on the diagram of FIG. 5 is generated. As already stated a signal is applied to motor 65 of tuning stub ϕ_3 which drives the fin 46 of tuning stub ϕ_3 so as to increase its positive reactance contribution when the impedance is on the left hand side of the vertical axis, and decrease the positive reactance contribution when the input impedance has a positive reactive component. Limit switches 66, one of which is shown and designated 78, on FIG. 8 are introduced to allow tuning stub ϕ_3 only to introduce positive reactance and thus this simple system performs the required function.

The remaining problem is one of automating a double stub tuner composed of tuning stubs ϕ_1 and ϕ_2 for the case in which the load impedance viewed from reference plane Y lies in initial shaded upper portion of the impedance diagram values of FIG. 6. It can be deduced from impedance diagram manipulations that the scheme shown in FIG. 8 will automatically adjust tuning stubs ϕ_1 and ϕ_2 to match the systems irrespective to the initial reactance contributions of the tuning stubs ϕ_1 and ϕ_{input} and the impedance of the load provided limit switches are incorporated to restrict the possible reactance contributions of the tuning stubs ϕ_1 and ϕ_2 to the values given above. stub the

The difference of the outputs of detectors 27 and 25 provides a signal which is proportional to the horizontal coordinate of the impedance referred to plane X (See FIG. 7). When tuning stub ϕ_1 is misadjusted while stubs ϕ_2 and ϕ_3 are properly adjusted, the input impedance follows the unit circle and thus it is appropriate to drive tuning stub ϕ_1 so as to increase its reactance contribution when this signal is negative and vice-versa. The situation with tuning stub ϕ_2 is some-

what more complicated but it can be shown that it is appropriate to drive tuning stub ϕ_2 with a signal proportional to the vertical coordinate of the impedance viewed from reference plane X (See FIG. 1). This signal is generated by subtracting the outputs of detectors 26 and 24.

Referring again to FIG. 8, the outputs from the detectors 24 to 27 are fed to inverting amplifiers 81 to 84 as shown in FIG. 8. The signals from amplifiers 81 and 82 are fed to difference amplifier 88, while the signals from amplifiers 83 and 84 are fed to difference amplifier 87. The output from the difference amplifier 88 is further amplified by an inverting amplifier with adjustable gain 110 and an emitter follower output stage comprising transistors Q3 and Q4, to drive motor 65 of ϕ_2 , thus controlling tuning stub ϕ_2 in accordance with the difference of the outputs of detectors 24 and 26. Similarly, the output from the difference amplifier 87 is further amplified by an inverting amplifier with adjustable gain 100 and an emitter follower output stage comprising transistors Q1 and Q2, to drive motor 63 of ϕ_1 , thus controlling tuning stub ϕ_1 in accordance with the difference of the outputs of detectors 25 and 27.

The construction of the apparatus according to the present invention was found to be quite straightforward. As stated above the tuner consists of a main waveguide section 8 with three E-plane T junctions 10, 12 and 14. Due attention is paid to the equivalent circuit of each E-plane T junction 10, 12 and 14 as described in "Waveguide Handbook" by Marcuvitz, McGraw Hill, 1951, in determining the spacing of the T's to yield an effective $7/8\lambda_g$ electrical separation and in determining the probe locations. The lengths of the branch sections of the E-plane T junctions 10, 12 and 14 are chosen so as to reflect the proper reactance range variation when terminated by the variable short circuits or adjustable tuning stubs ϕ_1 to ϕ_3 . All variable short circuits or adjustable tuning stubs ϕ_1 to ϕ_3 are identical, but the length of branch waveguide 12 connecting tuning stub ϕ_2 is shorter than the branch waveguides 10 and 14 for tuning stubs ϕ_1 and ϕ_3 in view of the different reactance range required.

We claim:

1. In a microwave heating apparatus, comprising a microwave energy source, and a microwave heating means connected thereto for heating a material by exposure to microwave energy from the microwave energy source, a microwave tuning means forming the connection between the microwave energy source to the microwave heating means, the tuning means comprising a main waveguide section connecting the output of the

microwave energy source to the input of the microwave heating means, first, second and third branch waveguides connected to the main waveguide section at spaced positions therealong from the microwave energy source, first, second and third adjustable tuning stubs attached to the first, second and third branch waveguides respectively, four signal sensing probes attached to the main waveguide section at spaced positions therealong between the microwave energy source and the first branch waveguide two further sensing probes attached to the main waveguide section as spaced positions therealong between the second and third branch waveguides, four microwave detectors each connected to one of said four sensing probes, two microwave detectors each connected to one of said two further sensing probes, a control circuit connected to said four microwave detectors and to said first and second adjustable tuning stubs to adjust, in response to said four microwave detector outputs, the effective electrical lengths of said first and second adjustable tuning stubs, and a control circuit connected to said two microwave detectors and to said third tuning stub to adjust, in response to the outputs of said two microwave detectors, the effective electrical length of the third tuning stub, whereby the microwave tuning means, in combination with the microwave heating means presents a substantially non-reflecting microwave load to the microwave energy source.

2. Tuning means according to claim 1, wherein said first, second and third tuning stubs each comprise a circular cross-section waveguide each forming a butt joint with their respective said first, second and third branch waveguides, said first, second and third branch waveguides are rectangular in cross-section, symmetrical inductive irises partially match the resulting discontinuity presented to microwave energy between said first, second and third branch waveguides, said circular cross-section waveguides are each identical comprising two tubular sections joined by a lap joint forming a choke for reflected microwave energy therein, each circular cross-section waveguide contains a metal block of circular cross-section, rotatably mounted coaxially therein, with a diametrically disposed, short circuiting fin, and an annular slot forming a radial waveguide, and driving means, controlled by said control circuits, are coupled to said metal blocks to rotate them to angular adjust the short circuit fins in response to the outputs of said four and said two microwave detectors, thereby adjusting the effective electrical lengths of said first, second and third tuning stubs.

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