United States Patent [19]

Bosisio

[11] **3,731,038**

[45] **May 1, 1973**

[54] **ZERO-MODE MICROWAVE APPLICATOR**

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[22] Filed: **Feb. 22, 1971**

[21] Appl. No.: **117,538**

[52] **U.S. Cl.**.....**219/10.55,** 219/10.61

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

[58] **Field of Search**.....219/10.55, 10.61

[56] **References Cited**

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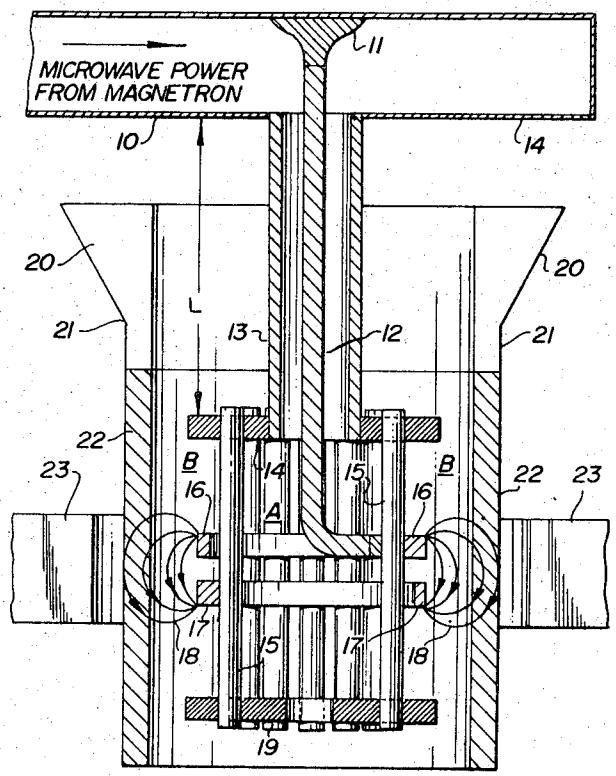
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Assistant Examiner—Hugh D. Jaeger
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[57] **ABSTRACT**

A fast-mode particularly a zero-mode microwave application for the heating, drying, curing or other treatment by microwave energy of workpieces containing lossy dielectric material having a fast wave microwave structure and microwave energization means connected to the structure to energize it such that a region adjacent said structure will contain a predominance of zero-mode or near zero-mode electric field energy.

1 Claim, 7 Drawing Figures



3 Sheets-Sheet 1

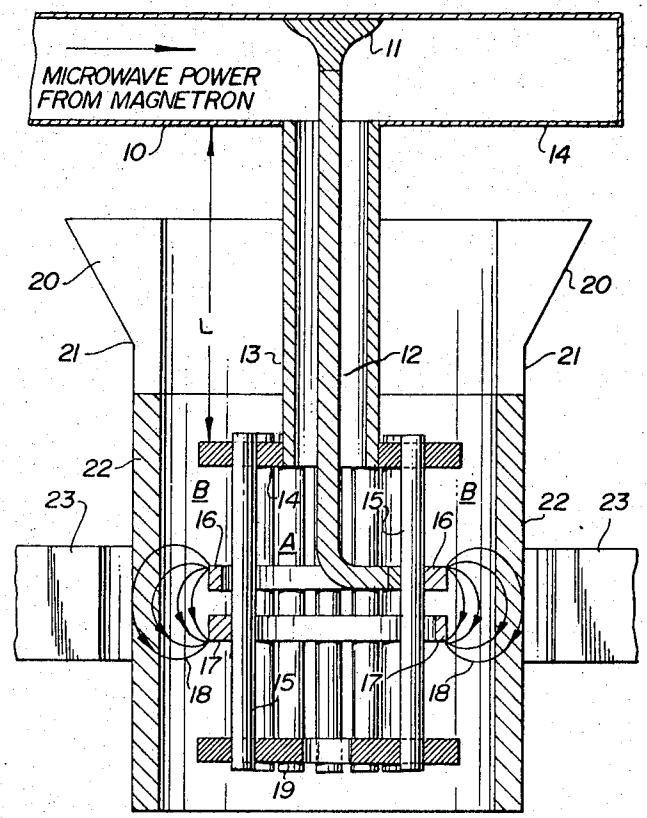


FIG. 1.

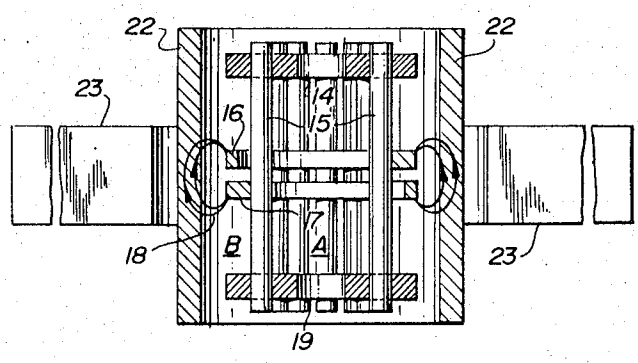


FIG. 2.

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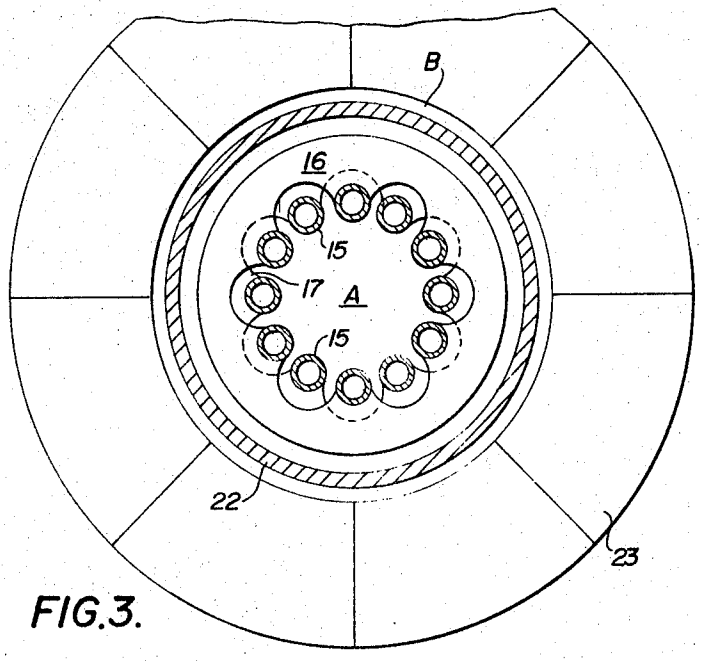


FIG.3.

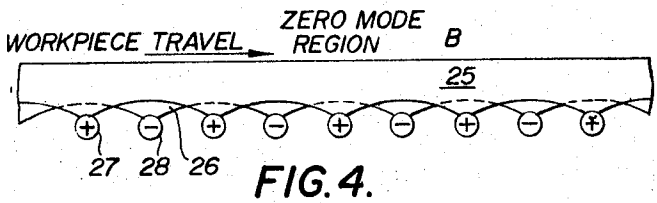


FIG.4.

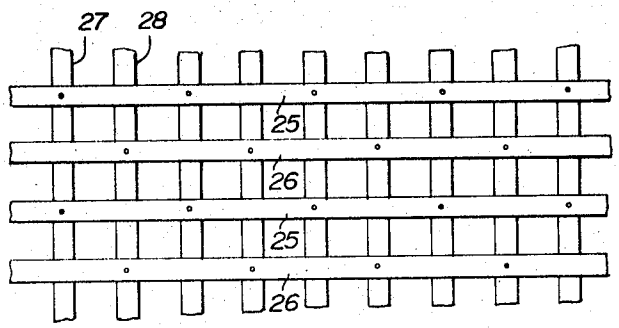


FIG.5.

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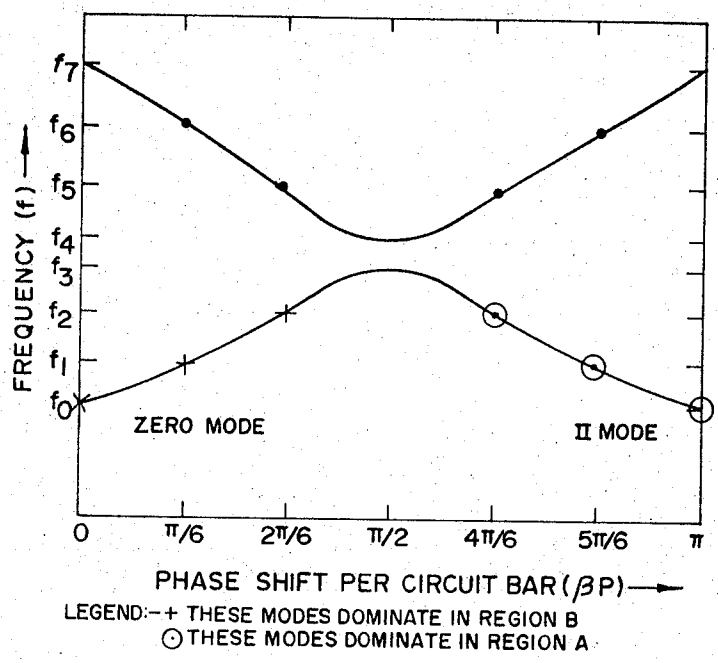


FIG. 6

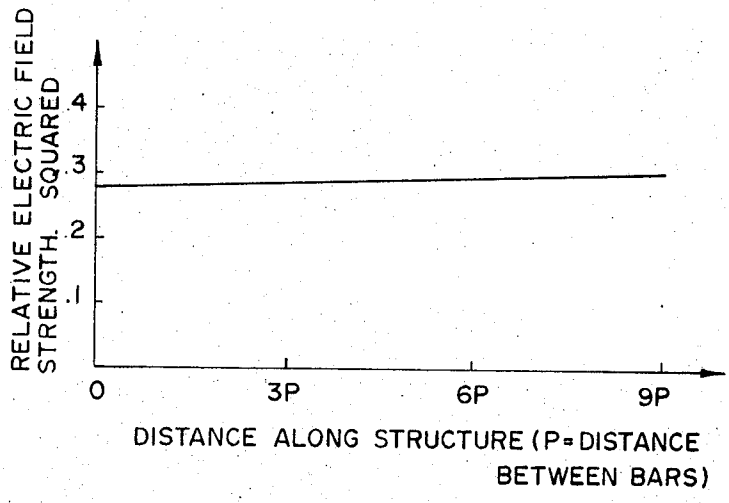


FIG. 7.

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ZERO-MODE MICROWAVE APPLICATOR

This invention relates to a fast-mode microwave applicator and more particularly to a microwave applicator in the zero-mode of electromagnetic energy transmission.

The purpose of a microwave applicator is to couple RF energy into a lossy dielectric work load for purposes of heating, drying, curing, etc. The required microwave energy is normally taken from a standard microwave transmission line via a suitable transition. In the presence of conducting walls, e.g., microwave ovens, modified transmission lines, waveguide terminations, standing waves are established due to reflected energy. These standing waves cause localized heating (hot spots) which is usually undesirable. Various methods are at present used to overcome this problem. Mode stirrers are used in microwave ovens and matched loads are used to terminate travelling wave type waveguide applicators.

It is an object of the present invention to provide a microwave applicator that has an even electric field distribution and that does not produce localized heating effects.

It is another object of the invention to provide a microwave applicator that can be readily used for heating, drying, or curing of various materials such as plastic, paper, rubber, wood materials and others materials that are well known by people versed in industrial microwave applications.

DEFINITION OF FAST MODE, SLOW MODE, AND ZERO-MODE

An electromagnetic mode is said to be "fast" whenever its phase velocity is greater than the velocity of an electromagnetic wave in free space. On the other hand an electromagnetic mode is said to be "slow" whenever its phase velocity is smaller than the phase velocity of an electromagnetic wave in free space. The phase velocity (V_{pH}) of a propagating mode is given by the following relation

$$V_{pH} = \omega/\beta \tag{1}$$

where ω is the radian frequency of the wave and β is its propagation constant. Equation (1) may be written in a different form in order to better understand the physical significance between a "fast" and a "slow" mode. Equation (2) below derives directly from equation (1) where f is the frequency of the mode and λ_g is the wavelength of the propagating mode.

$$V_{pH} = f\lambda_g \tag{2}$$

Therefore we have for a "fast" mode $(V_{pH})_F$ the following relationship

$$(V_{pH})_F > c \tag{3}$$

where c is the velocity of the wave in free space. The velocity c is related to the frequency (f) and the wavelength (λ_o) in free space by the following equation

$$c = f\lambda_o \tag{4}$$

From equations (4), (3), and (2) we have that

$$(\lambda_g)_F > \lambda_o$$

where $(\lambda_g)_F$ is now the wavelength of the "fast mode." In a similar manner we can derive the following relationship between the wavelength of a "slow" mode [$(\lambda_g)_S$] and the wavelength λ_o.

$$(\lambda_g)_S < \lambda_o$$

By "near zero-mode" we mean a mode that is essentially close to $\beta = 0$ but not necessarily at $\beta = 0$. The expression "fast-mode" as designated above has been used in the technical literature, and in particular by J. F. Gittins in the book "Power Travelling Wave Tubes" the English Universities Press Limited, 102 Newgate Street, London, E. C. I. on page 194.

These and other objects of the invention are achieved by a microwave applicator operating in or near the "zero mode" of electromagnetic energy in periodic wave structures. The zero mode has a propagation constant equal to zero and its wavelength on a periodic wave structure is infinite. The near-zero modes have very long wavelengths and may also be used with shorter workpieces.

In drawings which illustrate embodiments of the invention,

FIG. 1 is a cross-section of a microwave applicator arrangement for circular cross-section or tubular workpiece,

FIG. 2 is a view in cross-section of the fast-mode applicator,

FIG. 3 is a transverse cross-section of the apparatus of FIG. 2,

FIG. 4 is a view of a linear fast-mode applicator for flat sheet workpieces,

FIG. 5 is a plan view of the apparatus of FIG. 4,

FIG. 6 is a Brillouin diagram of a fast-mode applicator structure of the type of FIGS. 1, 2, 3, and

FIG. 7 is the relative electric field strength at frequency f_0 (zero-mode) in region B of the apparatus.

Referring to FIGS. 1, 2, and 3, a fast-mode microwave applicator for tubular workpieces that require heating, drying, curing, or other microwave energy treatment, has an input waveguide **10** for introduction of microwave power from a suitable power source such as a magnetron. A transition from rectangular waveguide to coaxial, in this case a doorknob type transition **11** directs the energy to a coaxial section made up of inner conductor **12** and outer conductor **13** having a length L which in practice will be much larger than shown in FIG. 1. An even number of metal (conducting) rods or tubes **15** placed on a circle of given diameter are electrically contacted near their mid-plane by circular parallel transmission lines **16** and **17** in alternate fashion as can be seen specifically in FIG. 3. The central conductor **12** of the coaxial line makes contact with circular parallel transmission line **16** (FIG. 1) and the outer conductor **13** makes contact with end shorting plate **14** connected to the ends of all the rods. A second shorting plate **19** is connected to the other ends of the bars **15**.

The separation of the shorting (conducting) plates **14** and **19** determines the operating frequency of the fast-mode applicator. Although more than one frequency can exist for a fast-mode in a given structure it is usually the lowest mode which is of interest. The

region indicated as B has been found to contain for this configuration well defined fast-modes including the zero-mode. A typical workpiece **22**, in this case a tube of plastic extruded from plastic pellet feed hopper **20** and extruder **21** shown in symbolic form passes downward and encircling the zero-mode applicator. The fast-mode engenders a field **18** passing from transmission lines **16** and **17** and as these are unidirectional and symmetric, they pass consistently through the material. A strong heating effect is obtained by the electric field on the lossy material in the workpiece.

Because of the necessity for safety, i.e., there could be microwave leakage giving rise to adverse effects on operators, a radiation suppression **23** encircles the workpiece at the level of the circular transmission lines **16** and **17**. This suppressor consists of a structure forming radial rectangular waveguides below cut-off for the frequency being employed.

FIG. **4** shows a fast-mode applicator similar to that of FIG. **1** but where the device is extended linearly. Parallel transmission lines **25** and **26** are contacted respectively by conductors **27** and **28** of alternate polarities. A fast-mode and in particular zero-mode region B exists above the transmission lines in the area shown and a flat workpiece could pass over the lines and be subjected to the zero-mode or near zero-mode fields for any wanted operation involving microwave energy. FIG. **5** is a plan view of the apparatus of FIG. **4** but showing two sets of the transmission lines **25** and **26**. This would provide a greater drying working area. The apparatus would be suitably energized from a microwave source (not shown) and the length of the microwave treatment region could be as long as desired within practised limits.

A lossy dielectric workpiece uniformly about the fast-mode applicator (FIG. **1**) or on the upper surface of the linear type (FIG. **4**) will contribute to adding a uniformly distributed capacitance and resistance to each periodic element of the structure. The capacitance element will have the effect of lowering the frequency of the zero-mode or other fast-mode for a given applicator design but it cannot alter the general shape of the Brillouin diagram of the periodic structure. The resistive element of the dielectric material will lower the electric field amplitudes but it can in no way interfere with the Brillouin diagram of the structure.

It is usual practice to describe a periodic structure such as described in the above description by a Brillouin diagram. Information regarding its pass-bands, stop bands, phase velocity, and group velocity are contained in such a diagram. From such diagrams the frequencies at which the propagation constant is zero or near zero may be identified. FIG. **6** is a measured Brillouin diagram of the structure shown in FIG. **1**. At any frequency in a pass-band or at a band-edge the energy may propagate on the structure in different modes. For example at the band-edge frequency f_0, energy may propagate at $\beta P = 0$ (zero-mode), $\beta P = \pi$, 3π, etc. These modes are called the fundamental, first, second, . . . space harmonics. The fundamental and its space harmonics each have their own amplitude and propagate simultaneously at a given frequency. It is therefore most important in a microwave applicator of the type described above that the fundamental mode (zero-mode or near zero-mode) amplitude dominate in a given space. If this is not the case the space harmonics which do have a finite wavelength would under certain conditions create well defined maximum and minimum and the problem of localized heating would again arise.

It has been found that region B of the applicator shown in FIGS. **1, 2, 3** and also FIG. **4** contains modes with little or no space harmonic content. FIG. **7** is a plot of the relative electric field strength squared for the f_0 (zero-mode) frequency in region B. It will be seen that the field strength is close to constant and indicates that an applicator working in the zero-mode or other fast-mode would be practical and efficient.

What is claimed is:

1. A zero-mode microwave applicator for the heating, drying, or curing of workpieces containing lossy material comprising:

a. a first set of parallel conducting rods positioned in spaced relation at fixed distances in a circle,

b. a second set of parallel conducting rods interleaved alternately in the circle with the first set,

c. a first transmission line in the form of an annular conducting plate encircling the said rods and shaped to make electrical contact with the first set of rods,

d. a second transmission line in the form of an annular conducting plate parallel to the first and encircling the said rods and shaped to make electrical contact with the second set of rods,

e. shorting plates connected at each end of said rods, and,

f. microwave energization means comprising a coaxial transmission line, the center conductor of which makes electrical contact with one of the said transmission lines and the outer conductor with one of the said shorting plates.

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