United States Patent

[11] 3,560,695

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[21] Appl. No. **799,828**
[22] Filed **Feb. 17, 1969**
[45] Patented **Feb. 2, 1971**

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[54] **MICROWAVE APPLICATOR EMPLOYING A FLAT MULTIMODE CAVITY**
13 Claims, 19 Drawing Figs.

[52] **U.S. Cl.** **219/10.55,** 333/21, 333/73, 333/98, 219/10.61
[51] **Int. Cl.** **H05b 9/06,** H01p 1/16
[50] **Field of Search** 219/10.61; 333/83A, 83; 219/10.55

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Primary Examiner—J. V. Truhe
Assistant Examiner—L. H. Bender
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ABSTRACT: A microwave applicator is disclosed which is especially useful for treating thin films of dielectric material. The microwave applicator includes a flat multimode cavity having a pair of parallel broad walls closed on their sides by narrow sidewalls. The cavity is preferably excited in one of the $TE_{l,m,n}$ and/or $TM_{l,m,n}$ classes of modes, where l is 1, with an electric field vector of the excited classes of modes being generally parallel to the broad walls and of relatively high intensity in the midplane of the cavity. The cavity is reactively loaded with periodic elements for concentrating the frequencies of the aforementioned classes of modes near the frequency of operation to facilitate mode-stirring and to improve the time average impedance match to the cavity during mode stirring.

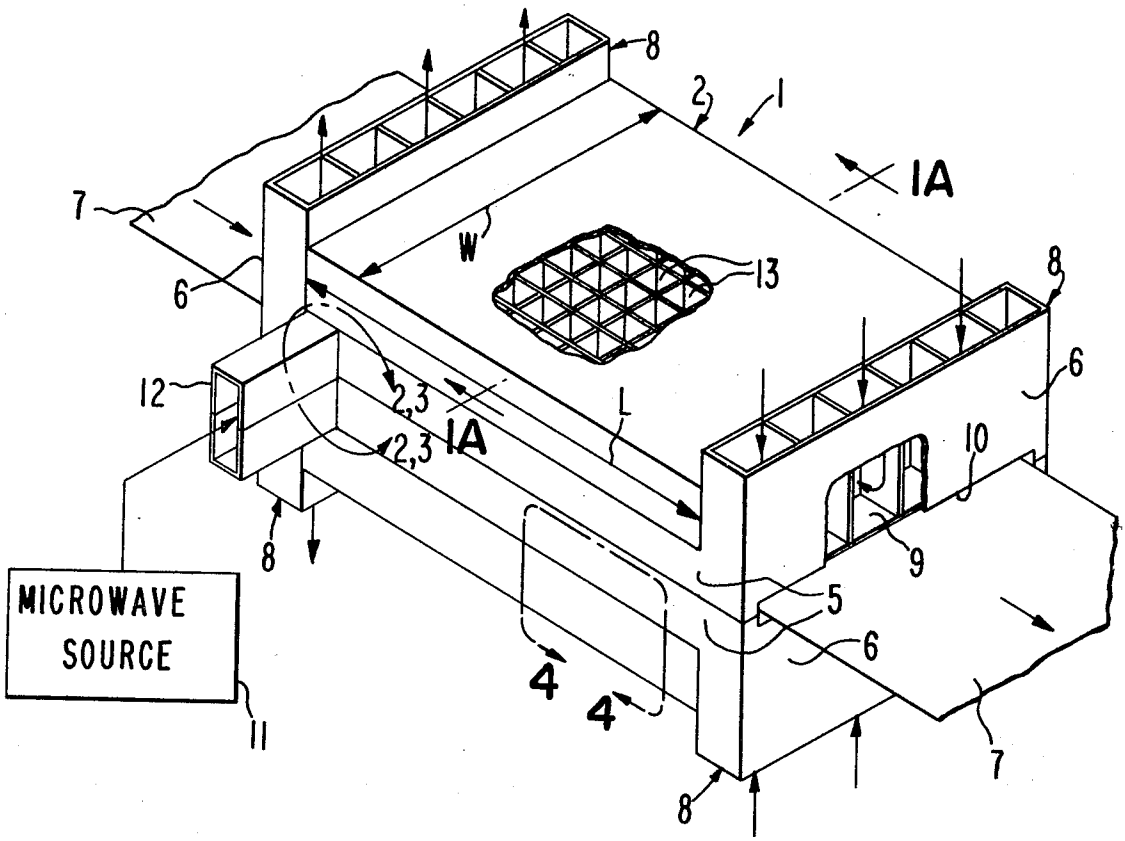


FIG.1

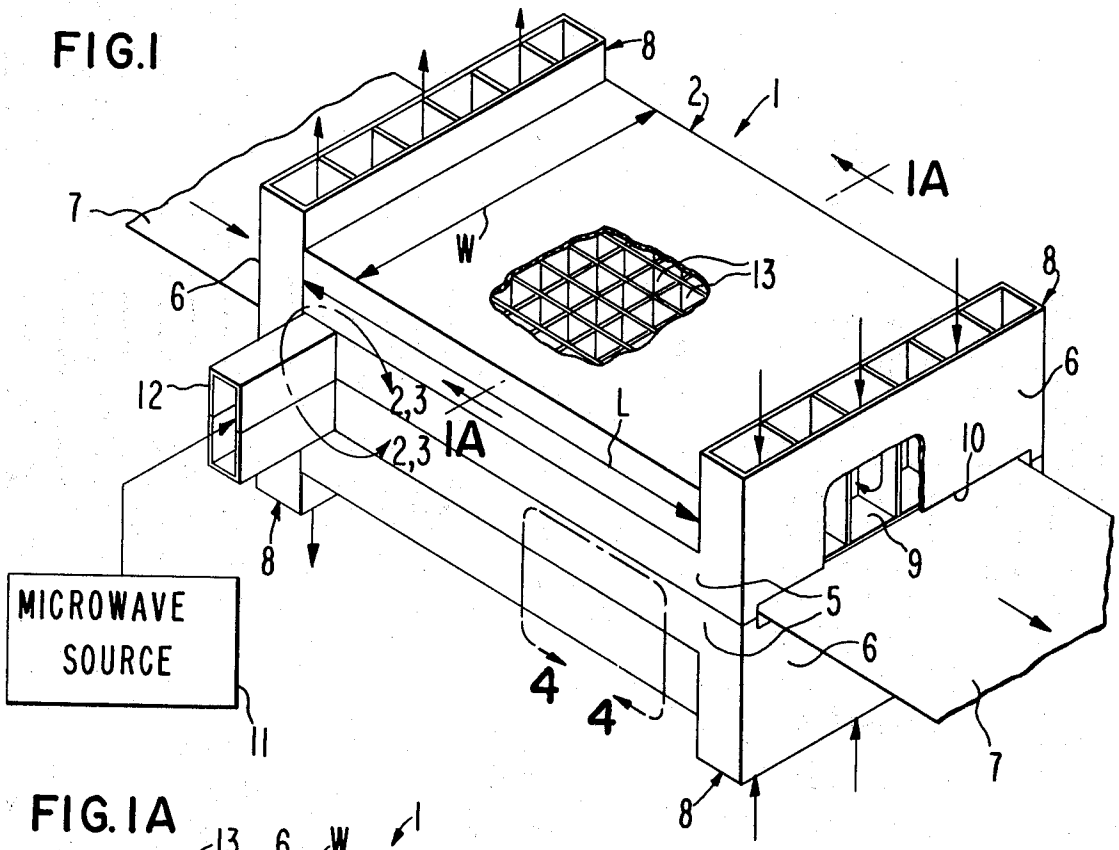
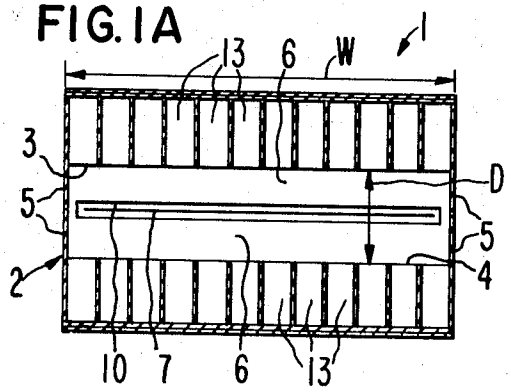


FIG.1A



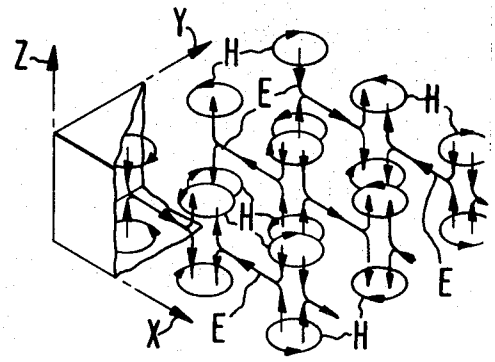


FIG.2

$TE_{l,m,n}$

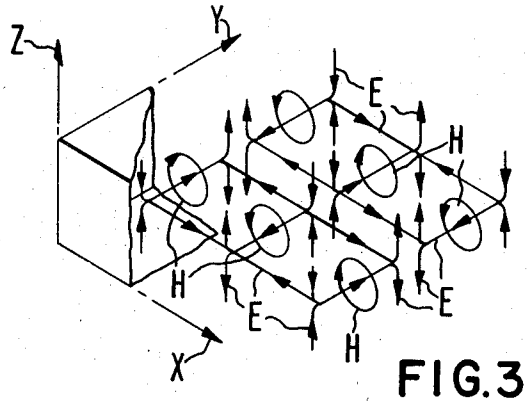


FIG.3

$TM_{l,m,n}$

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FIG. 4

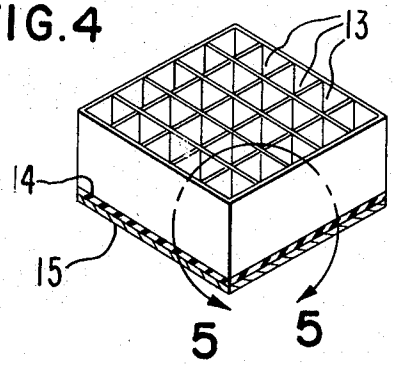
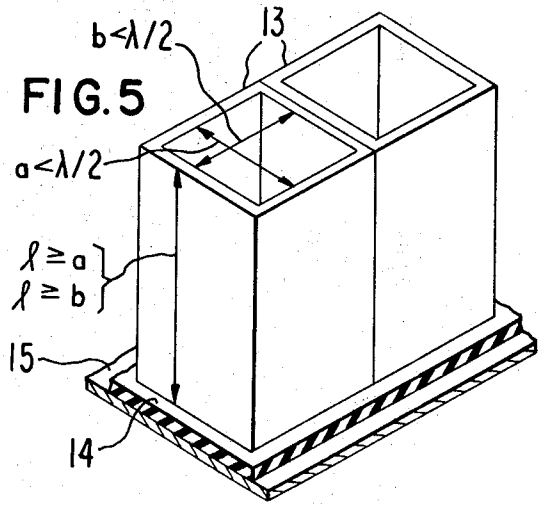


FIG. 5



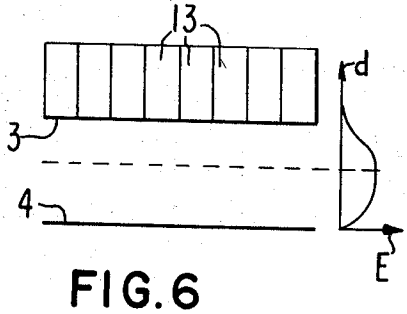


FIG. 6

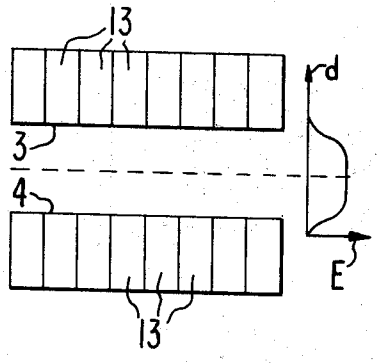
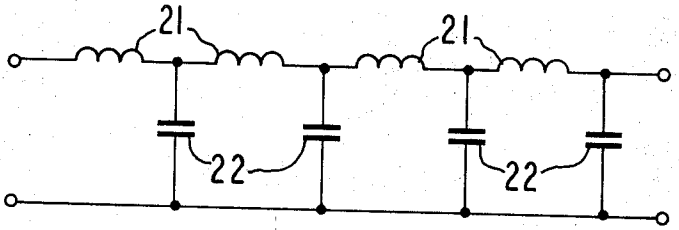


FIG. 7

FIG. 8



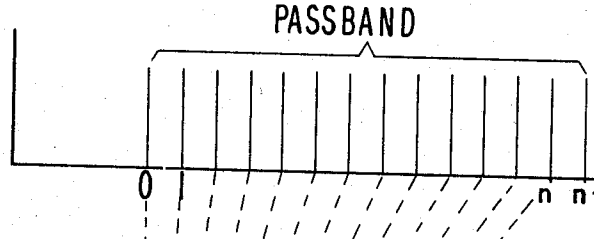


FIG. 9A
SPECTRUM OF AN UNLOAD CAVITY

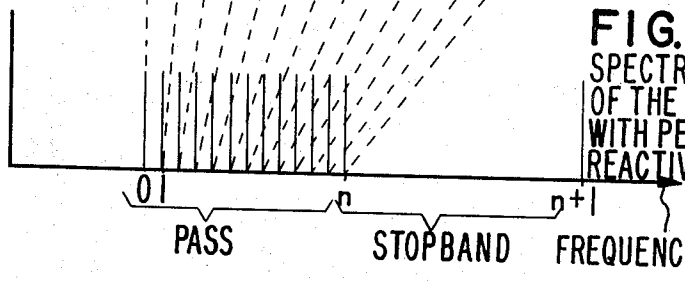


FIG. 9B
SPECTRUM OF THE CAVITY WITH PERIODIC REACTIVE LOADING

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FIG. 10

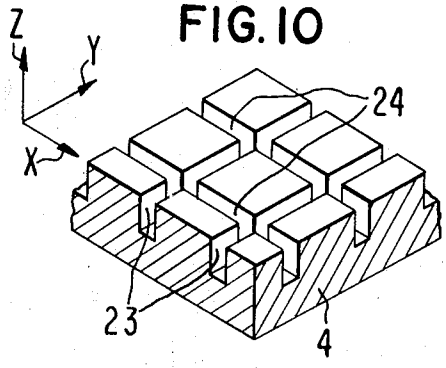
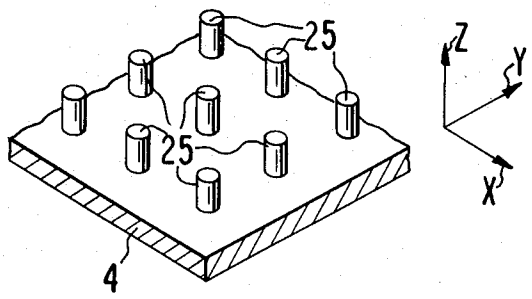


FIG. 11



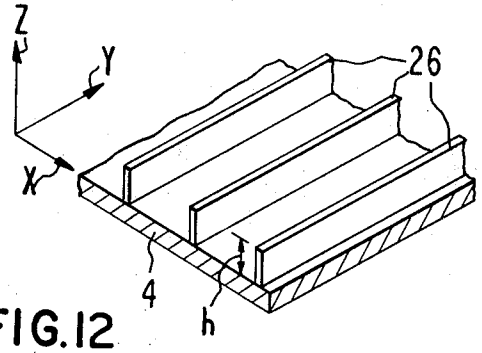


FIG. 12

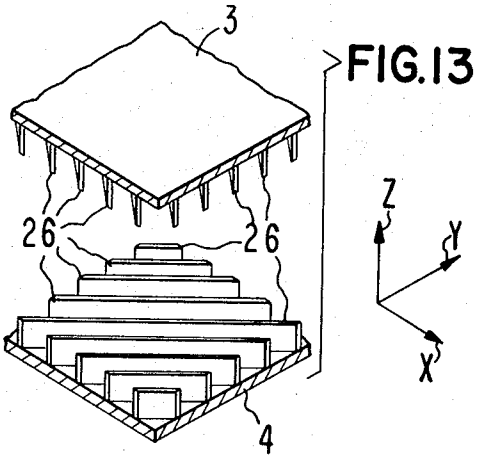


FIG. 13

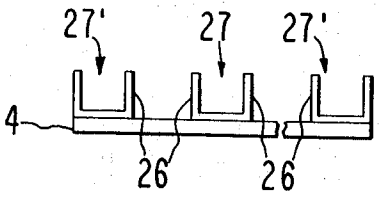


FIG. 14

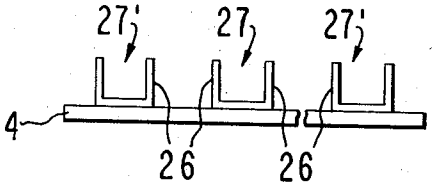


FIG. 15

FIG. 16

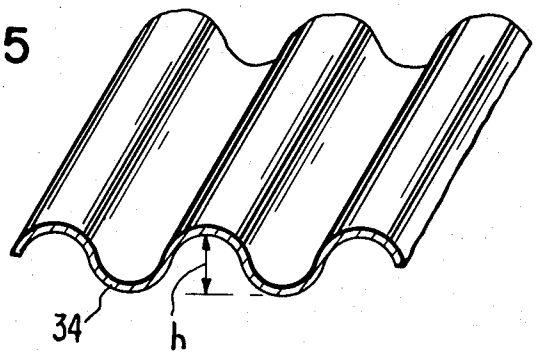
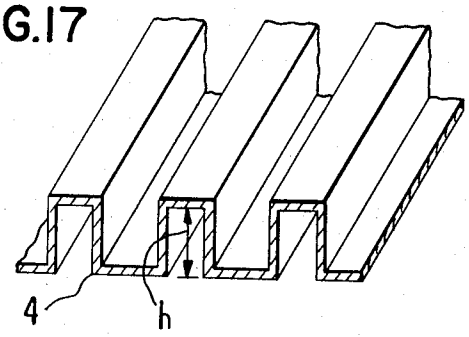


FIG. 17



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MICROWAVE APPLICATOR EMPLOYING A FLAT MULTIMODE CAVITY

DESCRIPTION OF THE PRIOR ART

Heretofore, multimode microwave cavity resonator applicators have been employed for treating thin webs of material. Such a multimode cavity applicator is disclosed in U.S. Pat. No. 2,650,291 issued Aug. 25, 1953.

Recently it has been found that if a multimode cavity applicator is made relatively flat, i.e., the dimension transverse to the plane of the sheet material being treated is reduced to between one-half and one wavelength, and the cavity is excited in either or both the TE*l,m,n* and TM*l,m,n* classes of modes, where *l* equals 1, that improved mode control can be obtained for the cavity to produce more uniform treatment of the web of material passing through the treatment zone of the cavity. Such a cavity applicator is disclosed and claimed in copending U.S. Pat. application 792,557 filed Jan. 21, 1969 and assigned to the same assignee as the present invention. Such a flat multimode microwave cavity applicator provides substantial advantages over the previous cavities and it is desirable to obtain these advantages also in those cases wherein the size of the web and limited space available would tend to limit the range of the mode designators, *m* and *n*, to undesirably low values. In other words, it is desirable to increase the "electrical" size of the cavity for a given physical size of the cavity.

SUMMARY OF THE PRESENT INVENTION

The principal object of the present invention is the provision of an improved microwave applicator structure.

One feature of the present invention is the provision of an array of reactive loading members in or coupled to the flat cavity applicator for reactively loading the microwave applicator cavity, whereby the desired TE*l,m,n* and TM*l,m,n* classes of modes are concentrated near the operating frequency of the cavity to facilitate mode-stirring in spite of a reduced physical size of the cavity resonator.

Another feature of the present invention is the same as the preceding feature wherein the reactive loading members comprise a two-dimensional clustered array of hollow conductive tubes with their axes directed generally perpendicular to the planes of the broad walls of the cavity with the inner ends of the tubes defining the inner conductive boundary of at least one of the broad walls of the cavity.

Another feature of the present invention is the same as the preceding feature wherein the transverse dimensions of the hollow tubes are dimensioned below cutoff for all modes at the operating frequency of the cavity.

Another feature of the present invention is the same as the first feature wherein the array of reactive loading members includes an array of generally parallel conductive fins affixed to the broad walls of the cavity with the plane of the fins being generally perpendicular to the broad walls of the cavity.

Another feature of the present invention is the same as the first feature wherein the array of reactive loading members is formed by corrugations in the broad wall of the cavity.

Another feature of the present invention is the same as the first feature wherein the reactive loading members comprise an array of slots or holes in the broad walls of the cavity.

Other features and advantages of the present invention will become apparent upon a perusal of the following specification taken in connection with the accompanying drawings wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic perspective view, partly broken away of a microwave applicator incorporating features of the present invention;

FIG. 1A is a sectional view of the structure of FIG. 1 taken along line 1A–1A;

FIG. 2 is a schematic line diagram depicting the TE*l,m,n* class of modes within a portion of the structure of FIG. 1 delineated by line 2–2;

FIG. 3 is a view similar to that of FIG. 2 depicting the TM*l,m,n* class mode pattern within that portion of the structure of FIG. 1 delineated by line 3–3;

FIG. 4 is a fragmentary schematic perspective view of a portion of the structure of FIG. 1 delineated by line 4–4;

FIG. 5 is an enlarged detailed perspective view of a portion of the structure of FIG. 4 delineated by line 5–5;

FIG. 6 is a composite schematic line diagram and plot of electric field intensity within a microwave applicator cavity incorporating features of the present invention;

FIG. 7 is a diagram similar to that of FIG. 6 depicting an alternative embodiment of the present invention;

FIG. 8 is a schematic circuit diagram for a two-wire transmission line depicting periodic series and shunt loading;

FIGS. 9A and 9B are spectral diagrams for a flat cavity without periodic reactive loading and for a flat cavity with periodic reactive loading and depicting the concentration of resonant modes within an operating band for the reactively loaded resonator;

FIGS. 10—13 are schematic perspective views of alternative reactively loaded cavity walls incorporating features of the present invention;

FIGS. 14 and 15 are alternative cross-sectional views of reactively loaded cavity walls employing channel members for loading elements; and

FIGS. 16 and 17 are schematic perspective views of alternative corrugated cavity walls for reactively loading same.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. 1 there is shown a microwave cavity applicator structure 1 incorporating features of the present invention. The applicator 1 includes a relatively flat multimode cavity resonator 2 having a pair of relatively broad parallel walls 3 and 4 closed on their side edges by two pairs of relatively narrow sidewalls 5 and 6 respectively. The pair of narrow end walls 6 are centrally apertured at 10 to define a slit for passage of a relatively wide thin web 7 of material to be treated with microwave energy. A typical web 7 may comprise a two mil thick continuous sheet of plastic film having a width of approximately 4 feet. The web 7 is pulled through the resonator by means of drive wheels, not shown, at a relatively high rate of speed as of 250 feet per minute.

A system of air ducts 8 is provided in each of the end walls 6 for ducting air through the cavity 2 in a direction preferably counter to the direction of movement of the web 7. The ducts 8 are closed off at their inner ends by plates 9 which define the lips of the openings 10 in the narrow walls 6. The inner sides of the ducts are open such that the individual ducts make a 90 turn for directing air in the direction of or counter to the direction of movement of the web 7.

The cavity resonator 2 preferably has internal dimensions depth D, width W, and length L, to support both the TE*l,m,n* and TM*l,m,n* classes of modes where *l* is 1 and *n* and *m* are preferably relatively large, as of greater than 5. These mode patterns are depicted in FIGS. 2 and 3 and are characterized by the E vector of the electric field being of maximum intensity midway between the broad walls 3 and 4 and being in a plane parallel to the broad walls, such that the electric field of the excited mode lies in the plane of the web 7 either parallel or transverse to the direction of movement of the web 7. To support the aforecited TM and TE classes of modes where *l* equals 1, the depth D of the cavity 2 is greater than half a wavelength and less than one wavelength.

The cavity 2 is excited with microwave energy supplied from a microwave source 11, such as a klystron amplifier with positive feedback to form an oscillator or magnetron oscillator. A typical source 11 would include a klystron amplifier having positive feedback to produce oscillation and supplying 25 kilowatts cw power at 2450 megahertz. The microwave energy is supplied to the cavity 2 via a rectangular waveguide 12, such waveguide opening into the cavity 2 through a rectangular opening at the corner of the cavity 2 with the

opening passing through the narrow sidewalls 5. The waveguide 12 is oriented with the broad walls of the waveguide 12 being perpendicular to the plane of the broad walls 3 and 4 of the cavity 2 such that the E vector in the exciting waveguide is parallel to the E vector to be excited within the cavity 2.

The top and bottom broad walls 3 and 4 of the cavity 2 are defined by the inner ends of a clustered array of tubular waveguide sections 13 dimensioned below cutoff at the operating frequency of the cavity 2. The tubular waveguide sections 13 are arranged with their longitudinal axes perpendicular to the plane of the broad walls 3 and 4 of the cavity.

Referring now to FIGS. 4 and 5 the clustered tubular waveguides 13, dimensioned below cutoff, are shown in greater detail. In a preferred embodiment, the tubular waveguides 13 are of rectangular cross section. However, a circular cross section would also provide the desired operation. In one embodiment, the tubular waveguides 13 are of square cross section, i.e., transverse inside dimensions *a* and *b* are equal and are both less than half a wavelength at the operating frequency of the cavity 2. In addition, the tubular waveguide sections 13 have a length *l* greater than one diameter and preferably between 3 and 4 diameters long. The outer ends of the tubular waveguides 13 are covered by an energy absorbing plate 14, as of asbestos, with an inorganic binder, to avoid back cavity resonances. The attenuator plate 14 is covered by a conductive plate 15, as of aluminum, to prevent radiation of microwave energy from the outside ends of the waveguides 13. Alternatively, the outside ends of the tubes 13 may be left uncovered for ventilating the cavity 2 and resistive cards diagonally disposed of the tubes would absorb the microwave energy which would otherwise radiate out the open ends of the tubes. Of course, if the tubes 13 are made sufficiently long the resistive cards would not be required.

The use of tubular waveguides 13, dimensioned below cutoff, for loading the top and bottom walls 3 and 4 appear as periodic reactive loading to the broad walls of the guide to produce a periodic reactive loaded wave supportive structure or cavity 2. The periodic reactive loading elements 13 tend to concentrate the resonant frequencies of the desired classes of modes near the operating frequency of the cavity 2, thus, facilitating mode stirring.

Referring now to FIG. 6 there is shown an alternative embodiment of the present invention wherein the clustered array of tubular waveguides 13, dimensioned below cutoff, are provided in only one of the broad walls of the resonator 2 such that the opposed broad wall 4 is merely a flat plate. In this case, the point of maximum electric field intensity E parallel to the web for the desired classes of modes of operation is moved slightly from the midplane toward the clustered array of waveguides 13 since some of the fields of the desired classes of modes can extend into the open ends of the waveguide sections 13. When both the top and bottom walls 3 and 4 are loaded with the waveguide sections 13, the point of maximum electric field intensity parallel to the web is at the midplane of the cavity 2, i.e., at the plane of symmetry between the two broad walls 3 and 4 as shown in FIG. 7. Another advantage of providing a symmetrical arrangement of the loading elements 13 is that the point of maximum electric field always occurs at the plane of symmetry, whereas in a nonsymmetrical structure as depicted in FIG. 6 the point of maximum electric field is frequency sensitive moving with frequency toward or away from the reactively loaded wall 3. In either case, the walls 3 and 4 can be moved closer together than for the case where the walls are not loaded since, as previously mentioned with regard to FIG. 6, some of the fields of the excited mode extend into the hollow waveguides 13.

This effect also occurs for the undesired classes of modes, wherein $l > 1$, and hence the upper limit on the depth D, is reduced accordingly.

Referring now to FIG. 8 there is shown a two wire equivalent circuit 8 useful for explaining the effect of the reactive loading elements 13. More specifically, the tubular waveguide sections 13 below cutoff may be considered an inductive reactance in series with the broad walls 3 and 4 of the cavity. This reactive loading appears as periodic inductive elements 21 in the circuit of FIG. 8. The capacitive elements 22 in the circuit of FIG. 8 may be considered as the capacitance between the broad walls of the cavity. The reactive periodic loading elements concentrate the frequencies of the desired resonant modes into narrow pass bands which are separated by empty stop bands in the manner as indicated in FIGS. 9A and 9B. In this manner a desirably high mode density within the operating pass band is obtained with a periodically reactively loaded cavity whose dimensions are much less than those of an unloaded cavity exhibiting the same mode density. This increase in the mode density within the operating passband improves the time-averaged impedance match to the cavity during mode stirring since the probability of the cavity dropping out of resonance as the frequency of excitation is reduced.

For example, referring now to FIG. 10, there is shown a reactively loaded broad wall 4 of the cavity 2 wherein the reactive loading elements comprise arrays of slots 23 and 24 having a depth preferably less than a quarter of a wavelength long at the operating frequency of the cavity 2. The slots 23 and 24 are arranged in an orthogonal array such that one set of slots 23 is directed parallel to the Y axis and the second array of slots 24 is directed parallel to the X axis, where the X and Y axes are defined in FIGS. 2 and 3. Alternatively, the slots 23 and 24 need not be arranged in an orthogonal array but may comprise only one parallel array 23 or 24 that need not be aligned with either the X or Y axis.

An alternative reactive loading arrangement is depicted in FIG. 11 wherein the reactive loading elements comprise conductive rods 25 each preferably less than a quarter wavelength long to form reactive loading elements. The rods 25 may be arranged in parallel arrays which are orthogonal to each other, i.e., one array being arranged in rows parallel to the X axis and the second array being arranged in rows parallel with the Y axis. As an alternative to the rods 25 being made of a metal, they may be made of a dielectric material for dielectrically loading the cavity, and thus, may be considered a shunt loading corresponding to shunt loading capacitive elements 22 of FIG. 8. Alternatively, the rods 25 need not be arranged in an orthogonal array but may be arranged in a closely packed pattern or in other patterns relative to the X and Y axes. Also the rods 25 may be replaced by an analogue, namely, an array of bores the size of the rods extending into the broad walls and positioned in patterns the same as for the rods 25.

Referring now to FIG. 12, there is shown an alternative periodic reactive loading embodiment of the present invention wherein the broad walls such as wall 4 is loaded by an array of conductive vanes 26 preferably having a height preferably less than a quarter wavelength. The vanes 26 may be symmetrically arranged in opposed walls 3 and 4 parallel to the Y axis or to the X axis or may be parallel to the X axis in one of the broad walls, for example, broad wall 3, and parallel to the Y axis in the lower broad wall 4. As in the embodiment of FIG. 11, the vanes 26 may be made of a dielectric material, such as alumina ceramic, for producing periodic shunt loading of the cavity 2.

Referring now to FIG. 13, there is shown an alternative embodiment of the present invention which is similar to that shown in FIG. 12 except that the vanes 26 are orthogonally disposed with respect to each other in the upper and lower broad walls 3 and 4, respectively, with the vanes being directed at 45° to both the X and Y axes in the plane of the walls 3 and 4. As in the embodiment of FIG. 12, the vanes 26, when they are conductive, preferably have a height preferably less than a quarter wavelength.

Referring now to FIG. 14, there is shown a convenient way to fabricate the vane structures of FIGS. 12 and 13 wherein the vanes 26 are provided by the parallel leg portions of channel members 27. The channel members 27 are, in the case they are conductive, fixedly secured to the wall 4 of the cavity

as by welding. The channel members **27** which are at the side edges of the wall **4** may be positioned flush with the edge of the wall **4** or may be positioned inwardly from the edge as by one-half a period as shown in FIG. **15**.

Referring now to FIG. **16** there is shown an alternative embodiment of the present invention wherein a broad wall **4** of the cavity **2** is periodically reactively loaded by corrugating the wall **4** more particularly, the broad wall is formed by a sinusoidally corrugated sheet of metal. The height *h* of the corrugations is preferably less than a quarter wavelength at the operating frequency of the cavity **2**. Alternatively, the cavity **2** may be periodically reactively loaded by making the corrugated wall **4** of FIG. **16** of a dielectric material and affixing the corrugated dielectric member to the inside surface of a conductive broad wall of the cavity **2**, such that the corrugations project from the broad wall toward the opposed broad wall of the cavity **2**.

Referring now to FIG. **17**, there is shown an alternative to the structure of FIG. **16** wherein the corrugations are more nearly of a square wave shape than they are sinusoidal. In another alternative embodiment, not shown, the corrugations of wall **4** are of a triangular wave shape.

As indicated in a number of places above the periodic reactive loading structure, as shown in FIGS. **4**, **10—17**, can be made of a dielectric material or of a conductive material.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be a made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

We claim:

1. In a microwave applicator, means forming a microwave cavity resonator having a pair of opposed broad walls closed on their sides by narrow sidewalls, the electrical spacing between said pair of broad walls of said cavity being greater than one-half wavelength and less than one wavelength at the frequencies of operation of said cavity, means for exciting the TE*l,m,n* and TM*l,m,n* classes of modes in said cavity where *l* is **1** and is in the direction extending between said pair of walls to produce an electric field of high intensity in a treatment zone between and generally parallel to said broad walls of said cavity, and means along at least one of said broad walls forming periodic inductive reactive loading of said cavity to produce a periodic reactively loaded cavity resonator having a higher mode density within its operating pass band than an unloaded cavity of the same physical dimensions.

2. The apparatus of claim **1** wherein said periodic reactive loading means comprises a two-dimensional clustered array of hollow conductive tubes having their longitudinal axes directed generally perpendicular to the plane of said broad walls of said cavity with the inner ends of said tubes defining the inner conductive boundary of at least one of said broad walls of said cavity.

3. The apparatus of claim **2** wherein the inside transverse dimensions of said hollow tubes are dimensioned below cutoff for TE and TM wave energy propagating axially of said tubes at the operating frequency of said cavity resonator.

4. The apparatus of claim **3** including means forming a resistive termination at the outer ends of said hollow tubes.

5. The apparatus of claim **2** wherein both broad walls of said cavity includes said array of conductive tubes with the inner ends of said tubes defining the inner conductive boundary of both of said broad walls of said cavity resonator.

6. The apparatus of claim **2** wherein said conductive tubes have a length in excess of their characteristic cross-sectional dimension.

7. The apparatus of claim **2** wherein said conductive tubes are of generally square cross section.

8. The apparatus of claim **1** wherein said reactive loading means includes an array of generally parallel fins with the plane of the fins being generally perpendicular to said broad walls of said cavity resonator.

9. The apparatus of claim **1** wherein said reactive loading means includes an array of generally parallel rods with the axes of the rods being generally perpendicular to the broad walls of said cavity resonator.

10. The apparatus of claim **1** wherein said reactive loading means includes an array of generally parallel slots formed in at least one of said broad walls of said cavity resonator.

11. The apparatus of claim **1** wherein said reactive loading means includes a corrugated structure with said corrugations projecting from one broad wall toward the opposed broad wall of said cavity.

12. The apparatus of claim **1** wherein said reactive loading means comprises an array of apertures in at least one of said broad walls of said cavity.

13. The apparatus of claim **1** wherein said reactive loading means provides periodic loading of said cavity along both its width and length.