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MICROWAVE AMPLIFIER FOR ELECTROMAGNETIC WAVE ENERGY INCORPORATING A FAST AND SLOW WAVE TRAVELING WAVE RESONATOR

Filed April 29, 1960

FIG. 1

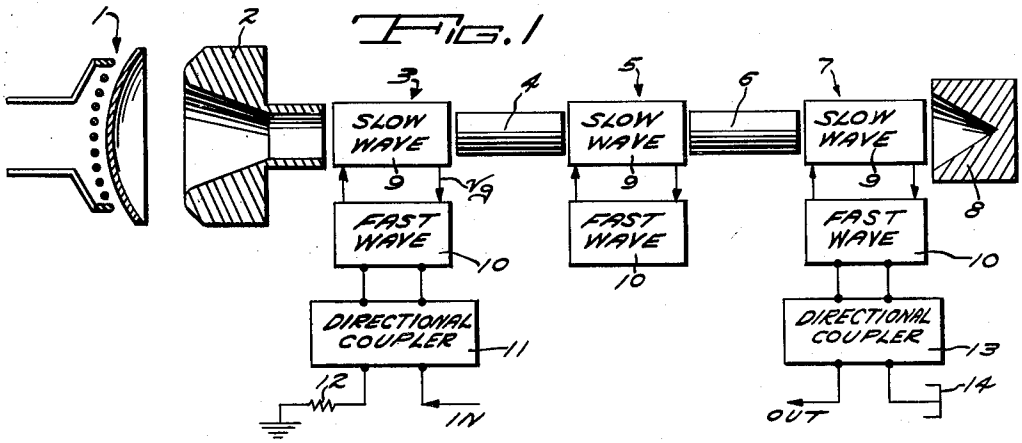
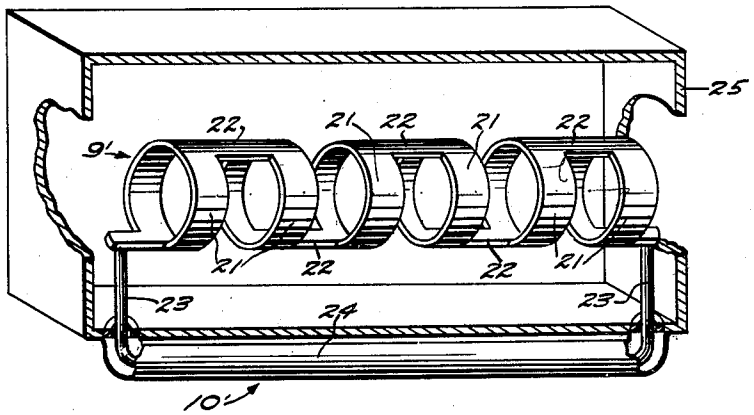


FIG. 2



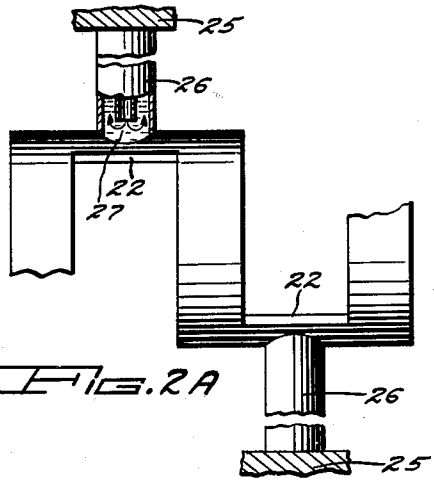
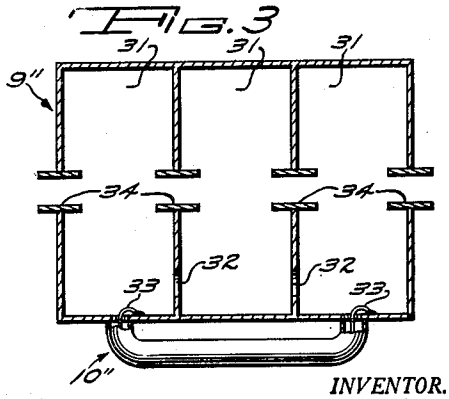


FIG. 2A

FIG. 3



INVENTOR.
Marvin Chodorow
BY
Wm. J. Nolan
ATTORNEY

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MICROWAVE AMPLIFIER FOR ELECTROMAGNETIC WAVE ENERGY INCORPORATING A FAST AND SLOW WAVE TRAVELING WAVE RESONATOR

Marvin Chodorow, Menlo Park, Calif., assignor to Varian Associates, Palo Alto, Calif., a corporation of California

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16 Claims. (Cl. 315—3.5)

This invention relates, in general, to velocity modulation methods and apparatus, and more particularly to a klystron type of microwave power amplifier tube embodying one or more extended interaction resonators.

In my co-pending U.S. patent application Serial No. 437,947, filed June 21, 1954, which is now U.S. Patent 2,945,155, granted July 12, 1960, there is disclosed a klystron amplifier tube wherein one or more of the resonators comprises a shorted slow wave transmission line structure for establishing a standing wave which interacts with the electron beam along the entire length of the structure. The use of such an extended interaction resonator has several important advantages over a conventional re-entrant type cavity resonator, including high efficiency and a large gain-bandwidth product. In the present invention, there is provided an improved extended interaction resonator of enhanced gain-bandwidth product capabilities, thus enabling improved tube design, especially for high power broadband applications.

The figure of merit determining the gain-bandwidth product of an extended interaction cavity may be conveniently expressed as

$$\frac{E^2L^2}{W}$$

where E is the effective electric field interacting with the electron beam, W is the total energy stored in the resonator and L is the length of the resonator. In the case of the structure described in the aforementioned patent application, the standing wave thereon can be resolved into two traveling waves, one moving in the same direction as the electron beam and the other in the opposite direction. Since the electron beam interacts primarily with the first wave, the second wave increases the stored energy W without contributing to the effective field E, thereby imposing an undesirable limitation on the gain-bandwidth product.

Accordingly, it is the principal object of the present invention to provide an extended interaction resonator for a velocity modulation tube in which substantially all of the stored energy is concentrated in the interacting wave.

Consider, now, an interacting slow wave transmission line structure in which the ends of the structure are coupled through an external transmission line to form a closed loop. If this structure is operated as a traveling wave resonator having a single sense of energy propagation around the loop, all of the energy stored in the slow wave structure can be made to contribute to the interacting field E, but none of the energy stored in the external line will contribute. Considerations of power flow continuity require that $v_{g_1}W_1=v_{g_2}W_2$, where v_{g_1} and v_{g_2} are the group velocities for the waves of the interacting line and the external line, respectively, and W_1 and W_2 are the respective stored energies per unit length in these lines. By selecting the transmission lines so that v_{g_2} is large compared to v_{g_1}, it is possible to concentrate substantially all of the stored energy W in the interacting wave, thereby obtaining a significant increase in the gain-bandwidth product.

Thus, a feature of the present invention is the provision of a traveling wave resonator for a velocity modulation tube comprising a first section of transmission line supporting a low group velocity wave for interacting with the electron beam, and a second section of transmission line supporting a high group velocity wave for coupling together the ends of said first transmission line section.

Another feature of the present invention is the provision of a traveling wave resonator in accordance with the preceding paragraph wherein said first section of transmission line has the effective configuration of a pair of cross-wound helices.

These and other features and advantages of the present invention will become apparent from a perusal of the following description taken in connection with the accompanying drawings wherein:

FIG. 1 is a schematic view of a klystron type of microwave partially schematic view of a klystron amplifier in accordance with the present invention,

FIG. 2 is an isometric view of a traveling wave resonator structure in accordance with the present invention,

FIG. 2A is an elevational view, partially in cross-section, of a stub support structure which may be used with the structure of FIG. 2, and

FIG. 3 is a cross-sectional view of another traveling wave resonator structure in accordance with the present invention.

Referring now to the klystron type of microwave amplifier of FIG. 1, an electron gun 1 is energized to provide a pencil-like electron beam centrally passing through a series of spans comprising focusing anode 2, input resonator 3, drift tube 4, intermediate resonator 5, drift tube 6 and output resonator 7, respectively, and finally terminating at electron collector 8.

Each of the resonators 3, 5 and 7 is shown as a novel traveling wave resonator comprising a slow wave interaction transmission line 9, and a fast wave transmission line 10 characterized by a group velocity substantially greater than that of line 9. For example, line 10 could be an air-filled coaxial line for which the group velocity is equal to the velocity of light at all frequencies, or a waveguide whose group velocity is closed to the velocity of light at the frequencies of interest. The two lines 9 and 10 are matched so that but little energy is reflected at the transitions therebetween. It is to be understood that the specific configurations used for the lines 9 and 10 may differ as between the different resonators, that any convenient number of intermediate resonators may be used, and that one or more of the resonators may be of a conventional type, such as standing wave resonator or a re-entrant cavity.

In the case of forward wave interaction (phase and group velocities both in the beam direction), the condition of resonance in the traveling wave resonator is that the total phase shift about the loop 9, 10 equals $2\pi N$, where N is an integer. Since line 10 is of a type characterized by a small dispersion (change in phase velocity with frequency), it is to be noted that most of the 2π change in total phase shift between adjacent modes is in the dispersive interaction line 9. This means that there is almost a full wavelength difference between adjacent modes, as compared to a half wavelength difference in the case of a standing wave resonator. This larger mode separation advantageously decreases the coupling between the beam and non-interacting modes which might otherwise cause undesired self-oscillations of the resonator.

The input microwave energy is fed to input resonator 3 via a directional coupler 11 having matched termination 12, in order to establish a single direction of energy propagation about the resonator as indicated by the group velocity vector v_g.

It is to be emphasized that sufficient loding must be provided in all of the resonators to prevent self-oscillation. Thus, it may be desirable, for example, to make resonators 3 and 5 from a relatively lossy material. In addition, the use of a variable directional coupler as

coupler 11 provides a convenient loading adjustment which does not introduce a backward wave. In principle, a directional coupler is not necessary for the intermediate resonator 5 since the current modulation on the electron beam will define a single sense of propagation; however, such a coupler may be desirable to also provide a means for varying the loading of the resonator.

Proper loading in the output resonator is provided, for example, by a power divider, or, as shown, a directional coupler 13 having a variable short-circuit termination 14 in order to compensate for mismatches in the external loading. A convenient feature of the output resonator is that the external loading required for maximum energy transfer from the beam may be sufficiently great that the low value of "Q" required for large overall bandwidth and prevention of self-oscillation is obtained without the necessity of introducing additional losses in the interaction structure.

In operation, the input microwave signal sets up a traveling wave in resonator 3 which interacts to velocity modulate the electron beam. The beam then enters the field-free drift tube space 4 wherein the velocity modulation is transformed into a current density modulation. This modulation is further intensified by interaction with the traveling wave of the intermediate resonator 5 and by subsequent passage through the drift tube space 6. Finally, the beam interacts with the traveling wave of output resonator 7 so that the beam modulation energy is extracted via coupler 13 in the form of a greatly amplified microwave signal.

In FIG. 2, there is shown a traveling wave resonator in accordance with the present invention comprising a slow wave interacting structure 9' and an external fast wave coaxial line 10'. One class of interacting structures found to be particularly desirable are those which are electrically equivalent to a pair of contra-wound helices. Examples of such structures, which are advantageously characterized by suppression of non-interacting space harmonics and an enhanced forward wave interaction, are found in my U.S. Patent 2,836,758. A preferred contra-wound structure 9' is of a simply fabricated and rugged notched-tube construction, and consists of a series of spaced axially-aligned parallel rings 21, each of which is joined by longitudinally extending bars 22 at diametrically opposed points respectively to the rings on each side thereof whereby the halves of the rings defined by said points provide two parallel paths for the propagation of wave energy.

The inner conductor 23 of coaxial line 10' is connected to the ends of the interacting structure 9', and the outer conductor 24 is connected in a vacuum-sealing manner to a cavity housing 25 partially surrounding the structure 9'. The propagating characteristics of the line 9' may be varied by changes in the size of the housing 25; and in some instances it may be preferable to omit the housing altogether. Further, it may be desirable to place the fast wave line 10' within the housing 25 in order to provide an advantageous control over the group velocity of interacting line 9' by means of the spacing between these two lines.

The heat dissipation, and hence power handling, capabilities of the structure 9' may be improved without detriment to its advantageous interaction properties by supporting it with a periodic array of stubs. As seen in FIG. 2A, the supporting stubs 26 extend perpendicularly from each ring 22 to the cavity housing 25. At low enough frequencies, stubs 26 may be made sufficiently large to be provided with water cooling channels 27, thus still further increasing the power handling capabilities of the structure.

To this point it has been assumed that the electron beam interacts with a forward wave. In some instances, however, it may be desirable to interact the beam with a backward wave. In this case, the slow wave line is operated so that the phase velocity of the interacting wave is

in the direction of the electron beam, but the group velocity (and hence the energy flow) is oppositely directed. However, the phase and group velocity in the external line remain in the same direction. The condition of resonance for establishing such backward wave operation with a single direction for the group velocity or energy propagation is that the *difference* between the phase shift in each of the two lines be equal to $2\pi N$, where N is an integer.

A resonator structure which may be conveniently operated for either backward wave or forward wave interaction is shown in FIG. 3. This structure comprises a rugged slow wave line structure 9'' consisting of a series of cavities 31 closely coupled by means of irises 32. The first and last cavities are coupled via inductive loops 33 through external fast wave coaxial line 10'' to complete the traveling wave resonator. The electron beam is directed through a series of longitudinally aligned passageways 34 in structure 9'' for interaction with the field of cavities 31.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be 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.

What is claimed is:

1. A microwave electron beam amplifier with improved gain-bandwidth product for amplifying electromagnetic microwave energy interacting with said beam comprising at least one distributed-interaction means with which said beam interacts at least one decoupling region through which said beam passes for decoupling said microwave energy from said beam and preventing transmission of said microwave energy into said decoupling region, said amplifier having means to prevent self-oscillation, said distributed-interaction means being an extended interaction traveling-wave resonator adapted and arranged to support a traveling electromagnetic wave therein, said traveling wave resonator comprising a first section of slow-wave structure adapted and arranged to support a traveling electromagnetic slow wave for interacting with the electron beam and a second section of fast-wave structure supporting a traveling electromagnetic wave having a large group velocity compared to the group velocity of said slow wave, said fast wave structure and said first section of slow-wave structure being coupled together at spaced-apart portions thereof and thereby concentrating on a per unit length basis a larger portion of the energy of said traveling electromagnetic wave in said traveling wave resonator in said interacting slow wave structure thereby providing an amplifier having an improved gain bandwidth product.

2. The amplifier as defined in claim 1 wherein said first section of slow wave structure comprises a series of coupled cavities.

3. A microwave amplifier in accordance with claim 1 wherein said traveling wave resonator means is a traveling-wave input resonator for velocity modulating the electron beam in variable accordance with an input signal fed to said impact resonator.

4. A microwave amplifier in accordance with claim 3 wherein a second said microwave amplifier further includes distributed-interaction traveling wave resonator means serving as an output traveling-wave resonator for extracting the modulation energy of said electron beam in the form of an amplified signal.

5. A microwave amplifier in accordance with claim 4 wherein said microwave amplifier further including a third distributed-interaction traveling wave resonator means serving as an intermediate resonator for further intensifying said current density modulation.

6. A microwave amplifier in accordance with claim 1 wherein said distributed-interaction means is an output

resonator for extracting the modulation energy of said electron beam in the form of an amplified signal.

7. A microwave amplifier in accordance with claim 6 wherein said microwave amplifier further includes another distributed-interaction traveling wave resonator means serving as an input resonator for further intensifying the current density modulation.

8. A microwave amplifier in accordance with claim 7 wherein said microwave amplifier further includes another distributed-interaction traveling wave resonator means as an intermediate resonator for further intensifying current density modulation.

9. A microwave amplifier in accordance with claim 1 and further including at least one directional coupler coupled thereto such that there is a single sense of energy propagation around said traveling-wave resonator.

10. A microwave amplifier in accordance with claim 1 wherein said second section of fast-wave structure is a coaxial transmission line.

11. A microwave amplifier in accordance with claim 1 wherein said second section of fast-wave structure is a waveguide transmission line.

12. A microwave amplifier in accordance with claim 1 wherein said first section of slow-wave structure is substantially electrically equivalent to a pair of contra-wound helices.

13. A micrcowave amplifier in accordance with claim 1 wherein said first section of slow-wave structure comprises a plurality of spaced axially-aligned parallel rings, each of which is joined in diametrically opposed points respectively to the rings on each side thereof.

14. A microwave amplifier in accordance with claim 13 further including a cavity housing partially enclosing said first section of slow-wave structure.

15. A microwave amplifier adapted and arranged to amplify electromagnetic microwave energy through cumulative interaction between said microwave energy and an electron beam traversing the axial extent of said microwave amplifier, said microwave amplifier including at least one electromagnetic field free drift tube region surrounding said electron beam and extending along one portion of the axial extent of said microwave amplifier, said drift tube region being a cut-off for said microwave energy, said microwave amplifier further including a traveling wave resonator, said traveling wave resonator having a first section including a slow wave structure extending along another portion of the axial extent of said microwave amplifier, said traveling wave resonator having a second section coupled to said first section including a fast wave structure coupled to spaced apart portions of said slow wave structure thereby forming said traveling wave resonator, said microwave amplifier further including means for preventing self-oscillation, said traveling wave resonator being adapted and arranged to support traveling wave electromagnetic energy therein, the group velocity of said traveling wave electromagnetic energy in said fast wave section being greater than the group velocity of said traveling wave electromagnetic energy in said slow wave section.

16. A microwave amplifier adapted and arranged to amplify electromagnetic microwave energy within a predetermined band of frequencies, through cumulative interaction between said microwave energy and an electron beam traversing the axial extent of said microwave amplifier, said electron beam thereby defining a central beam axis, said amplifier including a traveling wave resonator adapted and arranged to support traveling electromagnetic wave energy within said predetermined band of frequencies therein, said resonator having a first section including a slow wave structure extending along at least a portion of said central beam axis, said slow wave structure adapted and arranged to support traveling electromagnetic slow wave energy within said predetermined band of frequencies for interaction with said electron beam traveling along said slow wave structure, said resonator having a second section coupled to said first section including a fast wave structure adapted and arranged to support traveling electromagnetic fast wave energy within said predetermined band of frequencies, said traveling electromagnetic fast wave energy having a larger group velocity than the group velocity of said traveling electromagnetic wave energy within said slow wave structure thereby concentrating on a per unit length basis a larger portion of the energy of said traveling electromagnetic wave energy within said predetermined band of frequencies in said resonator in said first section than in said second section, said first section being coupled to said second section such that said second section forms an external feedback loop between the ends of said first section, said microwave amplifier further including at least one decoupling region coupled to said resonator along said central beam axis, said decoupling region being a cut off for microwave energy within said predetermined band of frequencies, said microwave amplifier being adapted and arranged to prevent self-oscillation thereof.

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GEORGE N. WESTBY, *Primary Examiner.*

ARTHUR GAUSS, BENNETT G. MILLER, *Examiners.*

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,192,430 June 29, 1965

Marvin Chodorow

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 2, line 38, for "closed" read -- close --; line 68, for "loding" read -- loading --; column 4, line 59, after "said" insert -- distributed interaction --; line 62, for "impact" read -- input --; line 64, strike out "a second" and insert the same after "includes" in lines 64 and 65, same column 4; column 5, line 27, for "micrcowave" read -- microwave --.

Signed and sealed this 22nd day of March 1966.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents