Jan. 29, 1963 E. O. SCHULZ-DU BOIS ET AL 3,076,148

TRAVELING WAVE MASER

Filed June 29, 1961

2 Sheets-Sheet 1

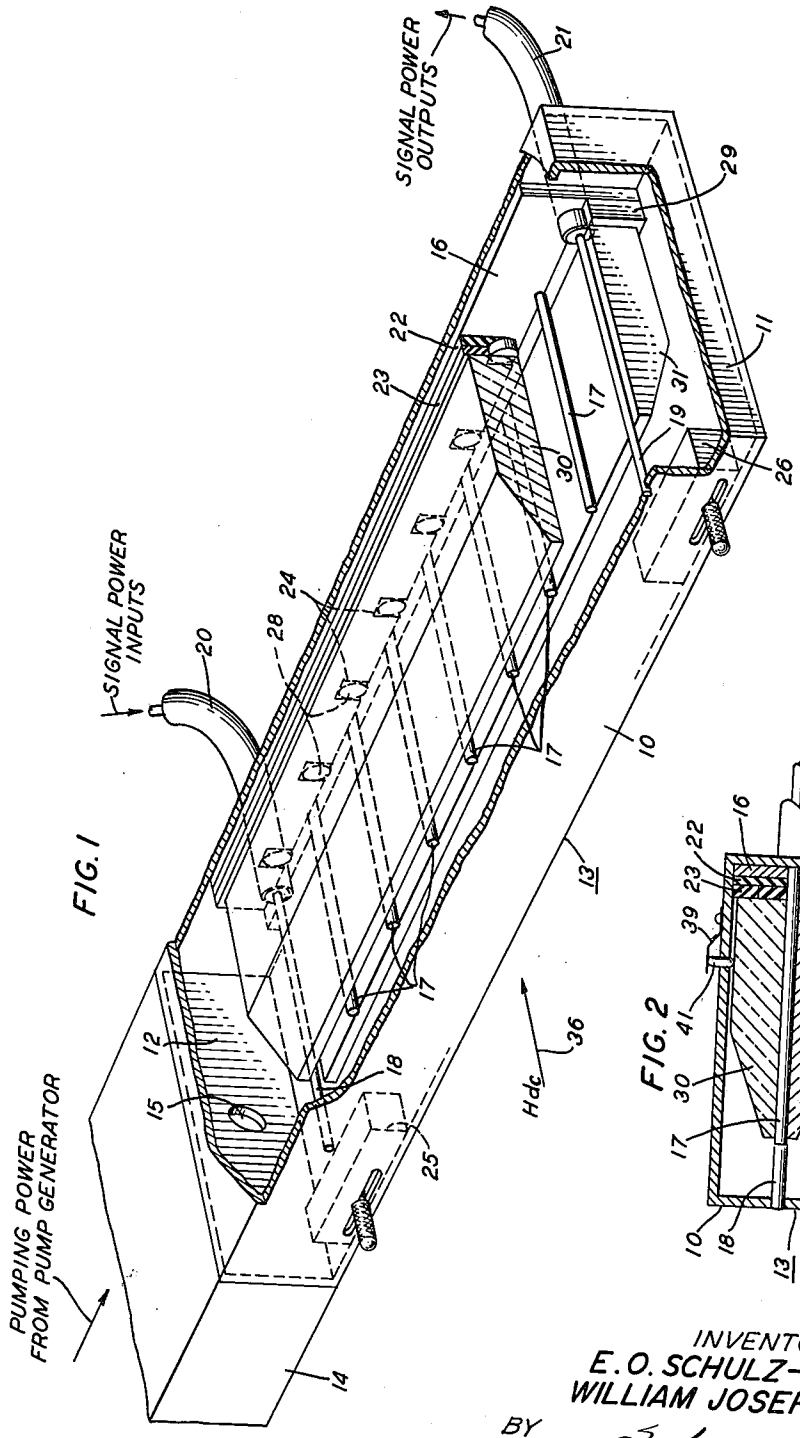


FIG. 1

FIG. 2

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2 Sheets-Sheet 2

FIG. 3

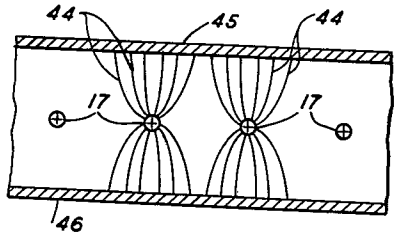
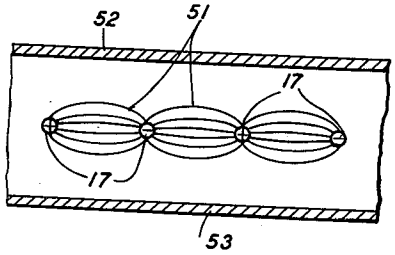


FIG. 4



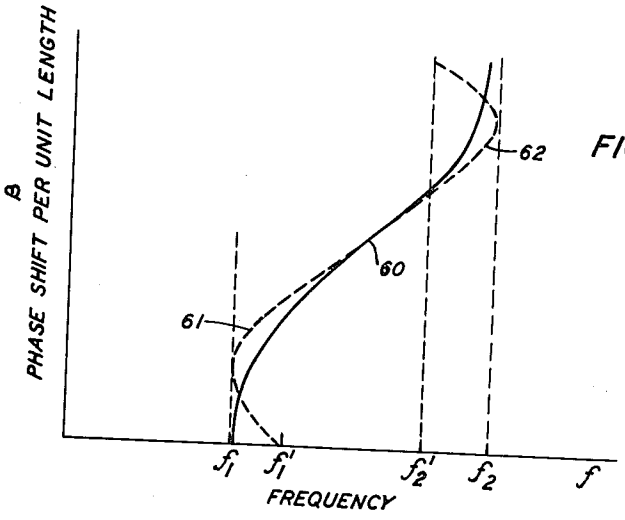


FIG. 5

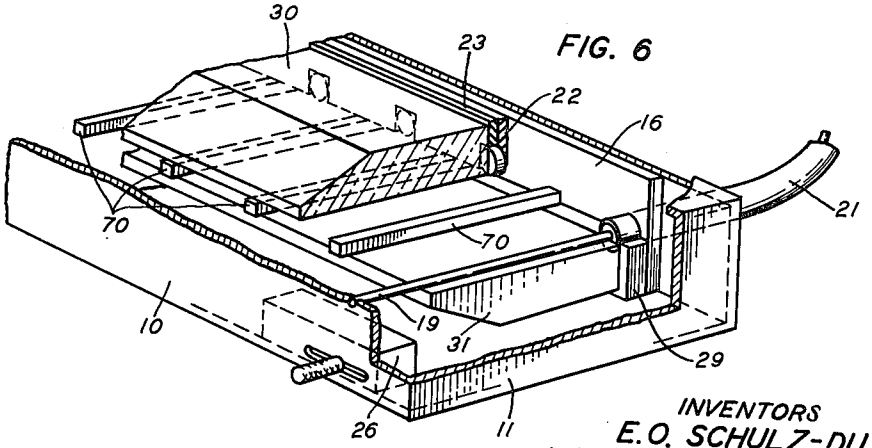


FIG. 6

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3,076,148

TRAVELING WAVE MASER

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4 Claims. (Cl. 330—4)

This invention relates to electromagnetic wave transmission devices, and in particular, devices in which amplification takes place by the stimulated emission of radiation from solid state media in propagating structures. Such devices are now generally termed traveling wave masers.

The three-level solid state maser, as proposed by N. Bloembergen in an article published in The Physical Review, volume 104, No. 2, pages 324–327, entitled "Proposal for a New Type Solid State Maser," employs a microwave pump signal to alter the thermal equilibrium of a paramagnetic salt in such a manner that an otherwise absorptive medium becomes emissive when stimulated by radiation at a signal frequency. Successful application of this principle to produce microwave amplification was reported by H. E. D. Scovil et al. in The Physical Review, 105, January 1957, page 762, using microwave cavities to couple the microwave radiation to the paramagnetic salt.

Microwave amplification can also be obtained by stimulated radiation from active material in a propagating structure. Efficient coupling of the microwave energy to the paramagnetic salt is obtained by slowing the velocity of propagation of the signal over an interval coextensive with the active material. The active material produces an equivalent negative resistance in the slow-wave structure and a propagating wave having an exponentially increasing amplitude is obtained. Such a device is described in the copending application by R. W. De Grasse et al., Serial No. 744,563, filed June 25, 1958, now Patent 3,004,225, issued October 10, 1961, and in an article by De Grasse et al. published in the March 1959 Bell System Technical Journal, pages 305 to 334 entitled "The Three-Level Solid State Traveling-Wave Maser."

The amplifier described in the De Grasse et al. article comprises a slow-wave comb-structure suitably loaded with active material and designed to operate at six kilomegacycles per second. When the techniques disclosed therein were extrapolated in an attempt to apply them to an amplifier intended to operate at lower frequencies, however, the exacting bandwidth-gain specifications desired for satellite communications systems could not conveniently be met based upon the prior art teachings.

One difficulty with the use of a comb-structure at lower frequencies is the resulting increase in size if the structure is simply scaled in dimensions to accommodate the lower frequencies. The nominal finger length is a quarter wavelength. This dimension, however, is along the direction of the steady biasing magnetic field and, consequently, is a determining factor in the size of the magnetic gap in the biasing circuit. Obviously, it is desirable that this gap be as small as possible. In accordance with this requirement, the actual finger length is typically reduced by capacitive loading at the finger tips. Such loading, however, also influences the overall electrical properties of the amplifier such as the upper and lower cut-off frequencies of the comb-structure, the shape of the phase

shift-frequency characteristic of the slow-wave structure and the gain of the amplifier. In particular, it has been found that capacitive loading of the comb finger tips can cause the phase shift-frequency response of the structure to bend back upon itself thereby converting the structure from a simple forward wave device to one having, over at least a portion of its operative bandwidth, two modes of propagation, one being a forward wave, the other being a backward wave. As used here, the term "backward wave" is meant to describe a type of energy propagation in one direction which is associated with phase propagation in the opposite direction.

The situation of having two modes of energy propagation present (i.e., forward and backward modes) is one of indeterminacy. Energy can travel in both of these modes. In particular, amplification can occur simultaneously in one mode in the forward direction and in the other mode in the reverse direction with some scattering of energy from one mode to the other occurring at both the input and output ends. This process is one of positive feedback. If its effect exceeds the losses in the system, the condition for oscillation is satisfied, that is, the device begins to generate oscillations and cannot be used for amplification as intended.

It is, accordingly, an object of the invention to decrease the size of the slow-wave structure at any given frequency by means of dielectric loading of the comb fingers.

It is a further object of this invention to control the frequency-phase characteristic and the bandwidth of a slow-wave structure by means of dielectric loading of the comb fingers in a manner so as to avoid the occurrence of a backward wave mode.

It is an additional object of this invention to increase the stable gain of the traveling wave masers by increasing the total useful volume of maser material.

These and other objects are realized in accordance with the present invention by shaping appropriately the cross-sectional geometry of the maser material. In particular, the maser material is tapered over a fraction of its width in the region of the finger ends. In a preferred embodiment of the invention, the maser material completely fills the amplifier housing from the base of the comb fingers to an intermediate point along the length of the fingers. Thereafter the maser material tapers to a fraction of its full height at a point near the open end of the comb-structure.

The tapering of the maser material permits the use of a greater volume of maser material, thus increasing the gain of the maser and decreasing the size of the slow-wave structure needed for a specified gain, but avoids the effects of foldover at the upper and lower cut-off frequency. The particular shape and dimensions of the tapered portion of the active material determine the value of the group velocity over the bandpass as a function of frequency. Thus, the overall electrical properties of a traveling wave maser amplifier can be readily controlled by suitable tapering of the maser material.

In a second embodiment of the invention the comb finger cross section is made square to increase the fraction of the total volume occupied by the maser material thereby increasing the amplifier gain per finger.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is a perspective view of the invention showing

the arrangement of the various components of the traveling wave maser amplifier;

FIG. 2 is a typical cross-sectional view of the embodiment of FIG. 1 showing, in particular, the geometry of the maser material;

FIG. 3 shows, by way of illustration, the field configuration along the slow-wave structure at the lower cutoff frequency;

FIG. 4 shows, by way of illustration, the field configuration along the slow-wave structure at the upper cutoff frequency;

FIG. 5 shows the phase shift-frequency characteristic of the slow-wave structure; and

FIG. 6 shows a portion of an alternative embodiment of the invention using comb fingers with square cross sections.

Referring to FIG. 1, there is shown a specific illustrative embodiment of a traveling wave maser amplifier in accordance with the present invention. Basically the amplifier comprises a waveguiding medum within which there is located a slow-wave comb-structure, a pair of particularly shaped slabs of active material of a type which is capable of amplifying by the stimulated emission of wave energy, and an isolator. In the particular embodiment of the invention shown in FIG. 1, the waveguiding medium comprises a length of rectangular waveguide **10** terminated at both ends by means of transverse conductive members **11** and **12**. The resulting cavity **13** is proportioned to support a standing wave of pumping power, which pumping power is derived from a pump generator (not shown) by way of a waveguide **14** and applied to cavity **13** through an aperture **15** in member **12**.

The slow-wave comb-structure comprises a conductive base member **16** disposed within cavity **13** along which there is mounted an array of conductive posts or fingers **17** which are orthogonally disposed with respect to the longitudinal axis of the section of rectangular waveguide **10**. Posts **17** which are, advantageously, copper plated tungsten rods are conductively secured to the base member **16**. Typically this can be done by soldering or brazing. The base member **16**, in turn, is disposed contiguous to one of the narrow walls of waveguide **10**. Alternatively, posts **17** can be secured in holes drilled directly in one of the narrow walls of guide **10**, the base member **16** then being an integral part of the waveguide wall.

Signal power is applied to the slow-wave structure and extracted therefrom by means of impedance matching networks of the type described in the copending application of J. M. Apgar, Serial No. 120,674, filed June 29, 1961. The networks comprise the end posts **18** and **19** which are, respectively, the extensions of the center conductors of the two coaxial transmission lines **20** and **21**. Line **20** serves as an input path for a signal wave which is to be amplified and line **21** serves to abstract from the device an amplified replica of the signal wave. The posts **18** and **19** which, advantageously, have the same diameter as that of the comb fingers **17** extend across cavity **13** in a direction parallel to the comb fingers and are conductively connected to the opposite narrow wall thereof. The distance between each of the end posts **18** and **19** and the next adjacent comb finger is equal to the finger-to-finger spacing of the comb filter. Movable blocks **25** and **26** are provided adjacent the end posts for fine adjustments of the impedance match.

Situated between the array of posts and the upper and lower wide walls of guide **10** are a pair of slabs **30** and **31** of active material whose particular geometry will be described in greater detail hereinafter. Various paramagnetic salts are suitable for use as the active or negative temperature material of maser devices of the general type described herein. The general nature of these materials is described in the aforementioned Physical Review article by N. Bloembergen. In many instances a doped paramagnetic salt, as described in United States Patent 2,981,894, issued to H. E. D. Scovil on April 25, 1961, can be advantageously used. As a specific example, the principles of the present invention can be embodied in devices having as the negative temperature material aluminum oxide which has an impurity content of approximately one-thirtieth of one percent of trivalent chromium. Materials of this type, referred to as "ruby" materials, are described in the De Grasse et al. article referred to above. More generally, however, any material capable of amplifying a signal wave by the stimulated emission of wave energy can be used. These materials, whatever their composition, will be referred to hereinafter as the active material or as the maser material.

Because the gain through the amplifier in the reverse direction is appreciable, a nonreciprocal loss mechanism is preferably included for stability. Such loss is provided by an isolator incorporated directly into the amplifier structure. The isolator comprises a ceramic spacer **22** which is situated adjacent to the base member **16** (or adjacent to the narrow wall of guide **10** in the event a separate base member is omitted and the posts **17** are mounted directly in the narrow guide wall). The ceramic spacer **22** extends longitudinally along cavity **13** the entire length of the slow-wave structure. Situated immediately adjacent spacer **22** is a second ceramic member **23** which also extends longitudinally substantially the entire length of the slow-wave structure. The member **23** is supplied with a plurality of apertures **24**, which are shown as squares in the embodiment of FIG. 1, into which there are inserted flat disks of gyromagnetic material **28**.

The term "gyromagnetic material" is employed here in its accepted sense as designating the class of magnetically polarizable materials having unpaired spin systems involving portions of the atoms thereof that are capable of being aligned by an external magnetic polarizing field and which exhibit a precessional motion at a frequency within the range contemplated by the invention under the combined influence of said polarizing field and an orthogonally directed varying magnetic field component. This precessional motion is characterized as having an angular frequency and a magnetic (or electric) moment capable of interacting with suitable electromagnetic fields. Typical of such materials are paramagnetic materials and ferromagnetic materials, the latter including the spinels such as, magnesium aluminum ferrite, aluminum zinc ferrite and the rare earth iron oxides having a garnet-like structure of the formula $A_3B_5O_{12}$ where O is oxygen, A is at least one element selected from the group consisting of yttrium and the rare earths having an atomic number between 62 and 71, inclusive, and B is iron optionally containing at least one element selected from the group consisting of gallium, aluminum, scandium, indium and chromium.

The gyromagnetic material and the maser material are magnetically biased by means of a common steady magnetic field H_{dc} (indicated by an arrow **36**) directed parallel to the rods **17**. The source of this field is not shown. However, it is understood that field H_{dc} can be supplied in any convenient manner well known in the art such as, for example, by using an electromagnet or a permanent magnet, and can, in addition, include means for varying the intensity of the field such as a potentiometer or a magnetic shunt.

An important aspect of the isolator design is the adjustment of the geometry of the gyromagnetic material in order to obtain gyromagnetic resonance at substantially the same frequency at which a paramagnetic resonance of the maser material occurs when subjected to the influence of the common magnetic biasing field H_{dc}. A geometry approaching a thin disk has been found to satisfy this condition. In a particular embodiment of the invention, circular, polycrystalline iron garnet disks with an aspect ratio of 8 to one are used. The disks are disposed within the apertures with their broad surfaces parallel to the narrow guide walls. The actual volume of the individual gyro-

magnetic elements is determined by the magnitude of the reverse loss that is required for amplifier stability and is a function of the aspect ratio of the disks and the physical limits imposed by the dimensions of the comb-structure. The remaining parameter is the location of the disks in the signal magnetic field. The high field intensity of the signal magnetic field at the shorted end of posts **17** calls for the placement of the disks in the plane near the base member **16**. The gyromagnetic material is, however, spaced a small distance away from the base member **16** by means of the ceramic spacer **22** to avoid undesirable interaction with the conductive base member **16** (or the guide wall in the absence of member **16**) and to simplfy fabrication of the isolator.

The gyromagnetic elements are longitudinally located between the comb posts **17** since the signal magnetic fields are most circularly polarized in this region. Finally, a compromise is accepted between high reverse loss on one hand and a high reverse-to-forward loss ratio on the other hand in choosing the transverse position of the disks. This is determined through test by varying the thickness of spacer **22**. Typically, isolators have been constructed having a reverse loss of 60 decibels and a forward loss of about 3 decibels. For a particular application an isolator has been made with a reverse loss in excess of 120 decibels while the forward loss in this case was as high as 10 decibels.

In a particular embodiment of the invention, spacer **22** and the member **23** have been made of sintered alumina, although any low-loss, nonmetallic material can be used. The sintered alumina, however, has the advantage that it has the same coefficient of expansion as ruby maser material generally used in such devices.

In an alternative arrangement, member **23** is omitted and the gyromagnetic material is cemented directly onto spacer **22**.

Located below the comb-structure is a second spacer **29** which extends longitudinally a distance equal to that of spacer **22** and which has a transverse dimension equal to the overall transverse dimension of spacer **22** and member **23**. Spacer **29** is advantageously made of the same material as spacer **22** and member **23** and is inserted to maintain the symmetry of the amplifier structure although it can be eliminated and the lower slab **31** of maser material extended to fill the region below the isolator assembly.

FIG. 2 is a typical cross-sectional view of the embodiment of FIG. 1 showing the cavity enclosure **13**, a comb finger **17**, base member **16**, dielectric spacers **22**, **23** and **29**, slabs **30** and **31**, input coaxial cable **20**, end post **18** and matching block **25**. Also shown are the dielectric pins **40** and **41** which extend through the cavity walls and hold slabs **30** and **31** in contact with the comb-structure under pressure from the spring-like members **38** and **39**.

The characteristics of the maser amplifier are determined to a large degree by the distribution of maser material along the slow-wave structure. For example, the gain of the maser varies as a function of the volume of the maser material used and inversely as the bandwidth of the slow-wave structure. This would suggest filling the entire cavity volume with maser material. To do so, however, would tend to lower the bandpass of the slow-wave structure without necessarily controlling its width. In addition, the indiscriminate addition of dielectric material tends to produce foldover of the frequency-phase shift characteristic which produces a backward wave over a region of the bandpass. Fortunately, the distribution of the magnetic and electric fields along the comb-structure permits a judicious distribution of maser material without any undue loss of gain. In general, the signal magnetic fields are a maximum at the shorted end of the fingers and a minimum at the open-circuited ends. Conversely, the electric field distribution is a minimum at the shorted ends of the fingers and a maximum at the open-circuited ends of the comb fingers. Consequently, to obtain maximum gain, full height loading of the cavity with active material is indicated near the base of the fingers where the RF magnetic fields are strongest.

The bandpass characteristic of the slow-wave structure exhibits an upper cut-off frequency which occurs at the frequency for which the fingers have an electric length of about a quarter wavelength and a lower cut-off frequency which is determined essentially by the capacity between the finger ends and the cavity walls. If the active material is extended full height over the entire length of the finger, the upper and lower cut-off frequencies are reduced. However, full height loading would be wasteful since there would be little increase in gain due to the relatively low intensity of the magnetic field at the finger ends and there would be no simple way of controlling the width of the bandpass by separately varying either the upper or lower cut-off frequency.

In the above-mentioned publication by R. W. De Grasse et al., it is shown that the electric field configurations at the upper and lower cut-off frequencies are distinctly different. In particular, it is pointed out that at the lower cut-off frequency the adjacent fingers are in-phase and the electric field pattern is as shown in FIG. 3.

FIG. 3 is a side view of a portion of the slow-wave structure showing the open end of the fingers. The "+" designation on each of the fingers **17** indicates an in-phase relationship for the signal wave. Because of this in-phase relationship, the electric field, indicated by the force lines **44**, extends from each finger to the guide walls. In FIG. 3 these are shown extending between two of the fingers and the upper and lower guide walls **45** and **46**, respectively.

At the upper cut-off frequency, adjacent fingers are 180 degrees out of phase and the electric field distribution is as shown in FIG. 4. As illustrated in FIG. 4, the electric force lines **51** extend between adjacent fingers **17** with substantially no electric field extending between the fingers **17** and the adjacent walls **52** or **53**.

In view of these distinctly different electric field configurations, end loading of the fingers with partial height dielectric material has been suggested. If placed immediately adjacent to the fingers, the effect is to increase the finger-to-finger capacity without greatly increasing the finger-to-wall capacity. Alternatively, if the dielectric material is placed adjacent to the wall, the effect is to increase the finger-to-wall capacity without substantially increasing the finger-to-finger capacity.

These arrangements, though basically sound, have practical difficulties which relate to the manner in which the frequency-phase shift curve is effected. In particular, a design based solely upon the effect upon the upper and lower cut-off frequencies has been found to be defective in that it has neglected to consider the effect upon the frequency-phase characteristic between the cut-off points. In particular, it has been found that foldover effects at either the high end or the low end of the response or at both ends are produced.

A preferred frequency-phase characteristic for the slow-wave structure is shown by curve **60** in FIG. 5. It is a single valued curve between the cut-off frequencies f_1 and f_2 and has a shape similar to an inverse cosine. Improper dielectric loading of the finger ends, however, can produce a curve that is double valued over an interval as illustrated, for example, by the dotted curve **61**. Whereas curves **60** and **61** both have the same cut-off frequencies, curve **61** folds back at frequency f_1 over an interval, reaching a zero phase shift condition at a slightly higher frequency f_1'. In the interval between f_1 and f_1', curve **61** is double valued and, in particular, the structure described by curve **61** supports a backward wave over the interval between f_1 and f_1'. The effect of this anomaly upon the operation of the amplifier is best illustrated by the table below which summarizes the behavior of the four possible waves that can be supported by a structure having a foldover region.

Table I

	Forward Wave Component	Backward Wave Component
Direction of Energy Propagation: Forward	Gain—Isolator operated properly.	Loss—Isolator attenuates backward wave component of forward propagating wave.
Reverse	Loss—Isolator attenuates forward wave component of reverse propagating wave.	Gain—Isolator ineffective against backward wave component of reverse propagating wave.

As seen from Table I, a forward propagating wave can lose a portion of its energy content by action of the isolator on its backward wave component within the frequency range between f_1 and f_1' due to the action of the isolator. What is perhaps more serious, however, is the fact that not all the energy reflected at the output of the amplifier is attenuated by the isolator as intended. Specifically, reverse propagating energy, having a backward wave component, experiences the full gain of the amplifier in its propagation through the amplifier due to the ineffectiveness of the isolator, producing a feedback mechanism capable of setting up oscillations, thus causing a disabling instability in the amplifier.

Foldover can also exist at the upper end of the passband, as indicated by the dotted curve **62**, resulting in conditions favorable for additional undesirable oscillations.

In accordance with the invention the problems incidental to foldover are avoided by the particular cross-sectional shape of the maser material. The problem, as indicated above, is to provide finger loading at both ends of the transmission band with a smooth transition between the upper and lower cut-off frequencies and, at the same time, to use a maximum volume of material in regions where the intensity of the magnetic field of the propagating wave is high so as to obtain maximum gain and to reduce the overall size of the comb-structure. This is accomplished by almost completely filling the volume above and below the fingers with maser material and by tapering the maser material over a fraction of its width in the region of the finger ends. As shown in FIGS. 1 and 2, the maser material is substantially the full height of the waveguide from the base of the fingers to an intermediate point along the finger length. Thereafter the maser material tapers to a fraction of its full height at a point near the open end of the comb-structure. The portion of the comb fingers extending beyond the maser material is of about five percent of the total finger length or less.

The shape and dimensions of the bevelled portion of the maser material is particularly important in determining the value of the group velocity of the signal wave over the bandpass as a function of frequency. Preferably, the group velocity is a constant over the band of interest. Changes in the group velocity can be effected by slight variations in the taper angle or in the relative dimensions of the bevelled portion.

In one particular embodiment designed to operate at four kilomegacycles per second, the tapered portion constitutes approximately 40 percent of the overall width of the maser material and the minimum height of the reduced height portion is approximately 19 percent of the full height of the material. More generally, and depending upon the bandwidth and gain specifications, satisfactory operation, as characterized by a frequency-phase shift response free of foldover, has been obtained where the tapered portion of the maser material constitutes from 20 to 50 percent of the overall width of the maser material and the minimum height of the reduced height portion varies from as much as 30 percent of the full height to as little as zero percent of the full height.

As shown in the figures, there is a small gap between the full height portion of the maser material and the adjacent wide wall of the amplifier housing. The gaps are provided to permit the insertion of the master material within the housing and to permit for expansion due to heating. The gaps, however, are preferably made as small as possible to avoid foldover near the lower cut-off frequency. Foldover tends to occur as the gap size increases.

It will be noted that the maser material is placed on both sides of the comb-structure in contrast to the traveling wave masers described in the De Grasse et al. copending application and the Bell System Technical Journal paper in which the maser material was only placed on one side of the comb-structure. At frequencies below approximately 10 kilomegacycles per second the maser materials tend to respond almost equally well to circularly polarized signal magnetic fields of either sense of rotation. Accordingly, by placing active material on both sides of the slow-wave structure, a one-third increase in decibel gain is realized. To do so, however, results in an amplifier with reciprocal gain. This places a severe burden on the isolator since short-circuit stability requires that the isolator reverse loss exceed twice the amplifier gain. However, by suitably shaping the maser material in accordance with the invention so as to carefully control the frequency-phase characteristic of the slow-wave structure thereby eliminating the possibility of spurious oscillations and by careful design of the isolator, the slow-wave structure can be more efficiently utilized by loading it with maser material above and below.

In one particular embodiment of the invention designed to operate at four kilomegacycles per second, and referred to hereinbefore, 30 decibels of gain was realized using 50 milliwatts of pumping power at approximately 30 kilomegacycles per second and a steady biasing field of 3300 oerstads.

In a second embodiment of the invention the cross section of the comb fingers is made square in an effort to increase the fraction of the total volume taken up by the maser material thereby increasing the gain per finger. This is illustrated in FIG. 6 which shows a portion of the embodiment of FIG. 1 with rectangular comb fingers **70**. In all other respects the device is as described above.

In all cases it is understood that the abovedescribed arrangements are merely illustrative of a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A traveling wave maser comprising a section of hollow, conductively bounded rectangular waveguide having a pair of narrow and a pair of wide walls, a coplanar array of parallel metallic posts located between said wide walls and longitudinally distributed along said guide, each of said posts having one end short-circuited to one of said narrow walls and the other end open-circuited to form a comb-like structure, at least one slab of maser material positioned adjacent the comb-like structure and extending longitudinally along said guide over an interval at least coextensive with said structure, said material having a maxiumum height which substantially fills the region between said posts and a wide wall of said guide from a first point adjacent said short-circuited end of said posts to a second point intermediate along said posts, said height gradually tapering off over an interval from said second point to a third point along said posts near the open-circuited end to a reduced height that is less than approximately 30 percent of the maximum height, said interval consitituting between 20 and 50 percent of the overall width of the maser material and means for establishing a steady magnetic field through said material.

2. The combination according to claim 1 wherein said

posts have a square cross section and wherein said maser material is in contact with a side of said square.

3. A traveling wave maser comprising a section of rectangular waveguide having a pair of narrow and a pair of wide walls, a coplanar array of parallel elements located between said wide walls and longitudinally distributed along said guide, each of said elements having one end short-circuited to one of said narrow walls and the other end open-circuited to form a comb-like structure, a slab of maser material positioned between said comb-like structure and each of said wide walls, said material extending longitudinally along said guide over an interval coextensive with said structure, each slab having a maximum height which substantially fills the region between said elements and a wide wall of said guide from a first point adjacent said short-circuited end of said elements to a second point intermediate along said elements, said height gradually tapering off over an interval from said second point to a third point along said elements near the open-circuited end to a reduced height that is less than approximately 30 percent of said maximum height, said interval constituting between 20 and 50 percent of the overall width of the maser material, and means for establishing a steady magnetic field through said material.

4. A traveling wave maser comprising a rectangular waveguide having a pair of narrow and a pair of wide walls, means for propagating signal wave energy within said guide, said means comprising a coplanar array of parallel elements, each of said elements having one end short-circuited to one of said narrow walls and the other

end open-circuited to form a comb-like structure along the direction defined by the longitudinal axis of said guide, means for applying input signal wave energy to one end of said signal wave propagating means, means for abstracting output signal wave energy from the other end of the signal wave propagating, means for applying pumping wave energy to the waveguide means, means for amplifying the signal wave by the stimulated emission of wave energy of the signal frequency, said means comprising a paramagnetic crystalline medium which in the presence of a biasing magnetic field and the pumping wave assumes a negative spin temperature at the signal frequency, said medium being positioned adjacent the comb-like structure having a maximum height which substantially fills the region between said structure and the wide walls of said guide from a first point adjacent said short-circuited end of said elements to a second point intermediate along said elements, said height gradually tapering off over an interval from said second point to a third point along said elements near the open-circuited end to a reduced height that is less than approximately 30 percent of said maximum height, said interval constituting between 20 and 50 percent of the overall width of said medium, and means for providing nonreciprocal attenuation for opposite directions of travel of the signal wave energy, said means comprising gyromagnetic material.

No references cited.