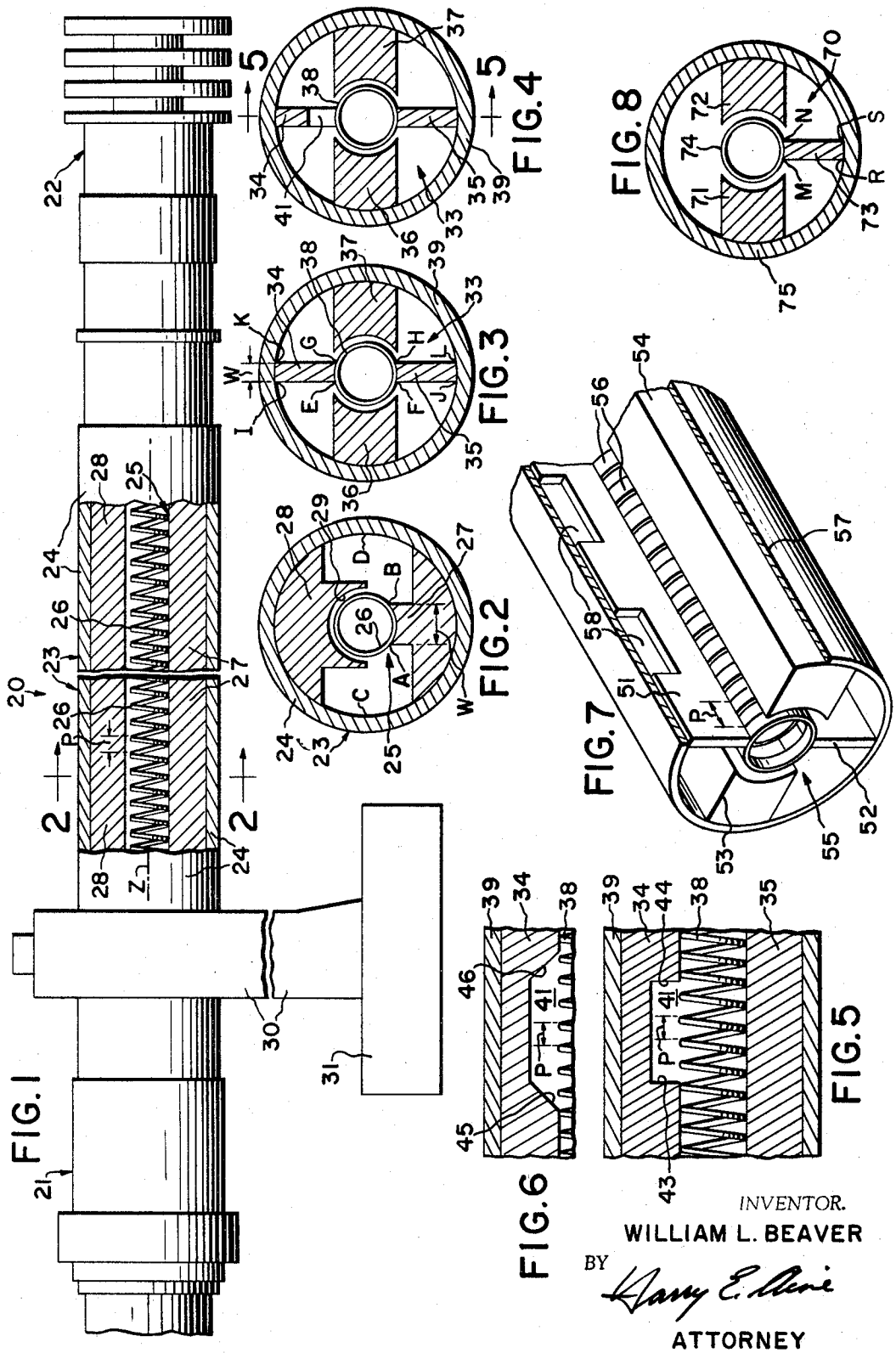
June 4, 1968 W. L. BEAVER 3,387,168

FIN-SUPPORTED HELICAL SLOW WAVE CIRCUIT PROVIDING MODE SEPARATION AND SUPPRESSION FOR TRAVELING WAVE TUBES

Filed Dec. 11, 1964 2 Sheets-Sheet 1



INVENTOR.
WILLIAM L. BEAVER
BY
Harry E. Aine
ATTORNEY

June 4, 1968 W. L. BEAVER 3,387,168
FIN-SUPPORTED HELICAL SLOW WAVE CIRCUIT PROVIDING MODE SEPARATION AND SUPPRESSION FOR TRAVELING WAVE TUBES
Filed Dec. 11, 1964 2 Sheets-Sheet 2

FIG. 9

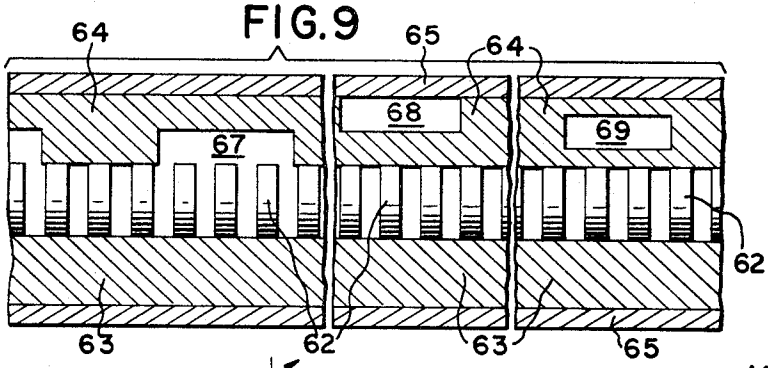


FIG. 17

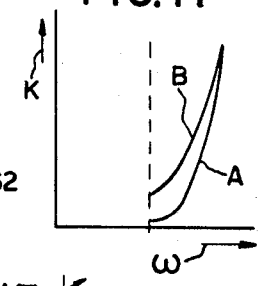


FIG. 10

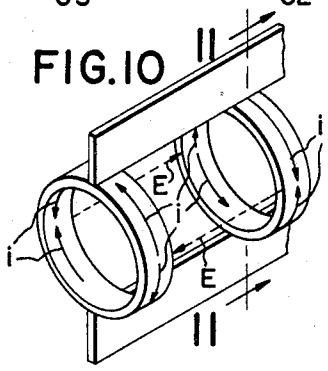


FIG. 12

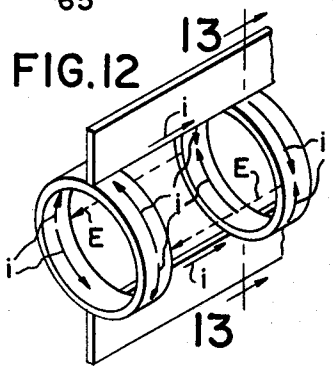


FIG. 11

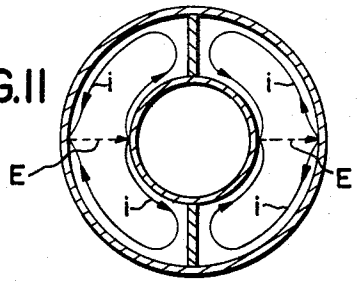
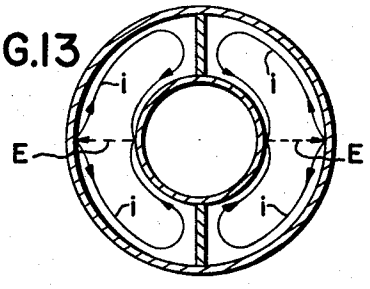


FIG. 13



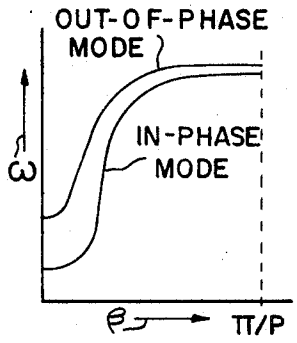


FIG. 15

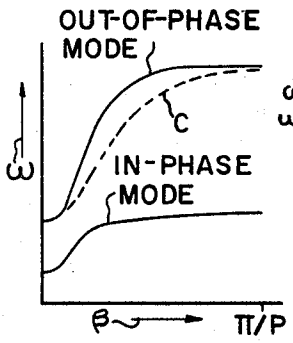
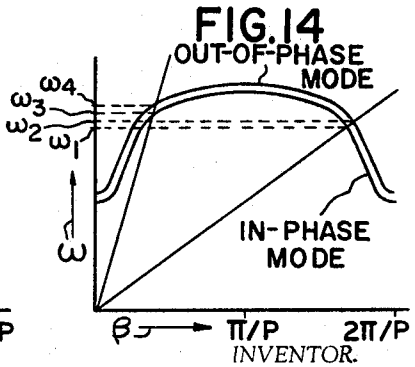


FIG. 16

FIG. 14



INVENTOR.
WILLIAM L. BEAVER
BY
Harry E. Aine
ATTORNEY

United States Patent Office 3,387,168 Patented June 4, 1968

3,387,168

FIN-SUPPORTED HELICAL SLOW WAVE CIRCUIT PROVIDING MODE SEPARATION AND SUPPRESSION FOR TRAVELING WAVE TUBES

William L. Beaver, Los Altos Hills, Calif., assignor to Varian Associates, Palo Alto, Calif., a corporation of California

Filed Dec. 11, 1964, Ser. No. 417,676
11 Claims. (Cl. 315—3.5)

ABSTRACT OF THE DISCLOSURE

A fin-supported helical slow wave circuit for TWT's. From 1 to 8 metal fins extend longitudinally through the waveguide to support the helix and provide improved thermal conductivity. One or more conductive loading ridges extending longitudinally throughout the waveguide increase the capacitance between helix and waveguide, resulting in increased bandwidth and lessened impedance shift throughout the frequency band. Slotted portions in the fins extending longitudinally over two or more consecutive periods of the helix provide mode separation and suppression which result in stable and predictable operating characteristics.

This invention relates in general to improved high frequency electron discharge devices and slow wave structures for electromagnetic waves and more particularly to improved high frequency electron discharge devices utilizing improved fin supported helical slow wave circuits.

The considerations which go into the final selection of a particular type of slow wave circuit (structure) for utilization in traveling wave tubes (TWT) of the amplifier and oscillator type are myriad and thus the ultimate structure chosen for any given application may be as varied in final design as the determining considerations are in number. A few of the prime considerations are thermal properties, ease of construction, useful bandwidth, operating power levels and stability of operation. The present invention involves a novel type of slow wave circuit which will be titled a fin supported helical slow wave circuit. This circuit has distinct thermal advantages over such prior art circuits as the rod supported helix and moreover this circuit has distinct fabrication advantages over the stub supported ring and bar type of slow wave circuit.

The present invention involves several novel forms of fin supported helical slow wave circuits having n number of elongated conductive loading ridges combined with n number of elongated conductive support fins, and novel mode separation and suppression techniques for such circuits. The number n is an integer having a value selected from the following list: 1, 2, 3, 4, 5, 6, 7, 8.

For the purpose of definition the terminology "fin supported helical slow wave circuit" is defined herein to include both the continuous helix structure and the spaced ring structure supported along the axial extent thereof by an elongated conductive fin or plane member which fin or plane member acts as a D.C. short (conductive path) between mutually opposed portions of adjacent turns of said helix or of said rings and wherein the transverse peripheral configuration of the helix or rings is preferably annular or circular although it includes any arbitrary transverse peripheral shape such as, square, rectangular, etc.

The particular mode separation and suppression means taught by the present invention are applicable to any slow wave circuit which has discrete fundamental modes of propagation having overlapping passbands within a given band of frequencies due to its particular geometric

configuration. The particular mode separation and suppression techniques disclosed by the present invention involve the physical perturbation of a given physical parameter of the slow wave circuit over a plurality of periodic lengths along the axial extent of the circuit. The mode separation and suppression techniques disclosed by the present invention are applicable to traveling wave tubes of both the amplifier and oscillator type. The present invention also provides a novel form of fin supported helical slow wave circuit which is particularly adapted to function in a traveling wave tube operating in a higher order passband.

It is therefore an object of this invention to provide a novel type of high frequency electron discharge device of the traveling wave type characterized by a capacitively loaded fin supported helical slow wave circuit.

A feature of the present invention is the provision of a novel fin supported and capacitively loaded helical slow wave circuit.

Another feature of the present invention is the provision of a slow wave circuit having discrete fundamental modes of propagation with overlapping passbands within a given band of frequencies and which incorporates certain novel mode separation and suppression techniques.

Another feature of the present invention is the provision of a fin supported helical slow wave circuit particularly adapted to function in a traveling wave tube operating in a higher order passband.

These and other features and advantages of the present invention will become more apparent upon perusal of the following specification taken in conjunction with the accompanying drawings wherein:

FIG. 1 discloses a novel traveling wave tube of the backward wave oscillator type incorporating the teachings of the present invention.

FIG. 2 is an enlarged cross-sectional view of the tube depicted in FIG. 1, taken along the lines 2—2 in the direction of the arrows;

FIG. 3 depicts a cross-sectional view, partly in elevation of an alternative fin supported helical slow wave circuit to that of FIG. 2 with a plurality of fins and loading ridges;

FIG. 4 depicts a sectional view of a fin supported helical slow wave circuit such as shown in FIG. 3, which incorporates mode separation and suppression techniques according to the teachings of the present invention;

FIG. 5 depicts a fragmentary longitudinal sectional view, partly in elevation, of the slow wave circuit depicted in FIG. 4, taken along lines 5—5 of FIG. 4 in the direction of the arrows;

FIG. 6 depicts a fragmentary cross-sectional view, partly in elevation, showing a modified embodiment of the circuit depicted in FIG. 5;

FIG. 7 depicts a fragmentary perspective view of a fin supported helical slow wave circuit such as depicted in FIG. 3 and incorporating a variation of the mode separation and suppression techniques disclosed in FIGS. 4–6;

FIG. 8 depicts a fin supported helical slow wave circuit particularly adapted to function in a traveling wave tube operating in a higher order passband;

FIG. 9 depicts a fragmentary longitudinal sectional view partly in elevation, of a fin supported helical slow wave circuit which incorporates various illustrative mode separation and suppression techniques;

FIG. 10 is a structural perspective view of a typical double fin supported helical slow wave circuit disposed within a cylindrical waveguide, not shown, and the accompanying current flow patterns and E-field configurations for what can be termed the out-of-phase mode at the upper cut-off frequency of the lowest passband;

FIG. 11 is a cross-sectional view of a typical double fin supported helical slow wave circuit of FIG. 10 taken along line **11—11** and disposed within a cylindrical waveguide showing the accompanying current flow patterns and E-field configurations for what can be termed the out-of-phase mode at the lower cut-off frequency of the lowest passband;

FIG. 12 is a structural perspective view of a typical double fin supported helical slow wave circuit disposed within a waveguide, not shown, and the accompanying current flow patterns and E-field configurations for what can be termed the in-phase mode at the upper cut-off frequency of the lowest passband;

FIG. 13 is a cross-sectional view of a typical double fin supported helical slow wave circuit of FIG. 12 taken along line **13—13** as disposed within a waveguide showing the accompanying current flow patterns and E-field configurations for what can be termed the in-phase mode at the lower cut-off frequency of the lowest passband;

FIGS. 14–16 are illustrative ω–β diagrams for various fin supported helical slow wave circuits;

FIG. 17 is an illustrative diagram depicting interaction impedance vs. frequency for a typical fin supported helical slow wave circuit with and without a loading ridge.

Referring now to FIG. 1, there is depicted a high frequency electron discharge device **20** of the traveling wave type and specifically of the backward wave oscillator type having a conventional electron gun structure **21** disposed at the upstream portion thereof and a conventional collector **22** disposed at the downstream portion thereof. Intermediate the electron gun and collector is a slow wave circuit **23** which includes a cylindrical waveguide **24** coaxially disposed about the electron beam axis Z. A conventional helix is supported along its axial extent by a conductive support fin **27** by any suitable metal joining technique such as, for example, brazing. Diametrically opposite the support plane or fin **27** is a conductive capacitive loading ridge **28** which also extends along the axial extent of the slow wave circuit. As shown more clearly in FIG. 2, the cylindrical conductive waveguide **24** surrounds the fin supported helical slow wave circuit and forms part of the vacuum envelope of the tube.

In order to optimize the effectiveness of the loading ridge **28** from an impedance standpoint and maximize capacitance while reducing the chance of voltage breakdown between the helix and the loading ridge **28** when used in a high power amplifier tube, the loading ridge is provided with a curved surface or face **29** facing the helix and having substantially the same curvature as the exterior periphery of the helix **26** and extending over the length of the helix. A conventional output circuit for electromagnetic traveling wave energy, such as waveguide **30**, in conjunction with a suitable vacuum sealed window assembly **31**, is employed to extract the electromagnetic traveling wave energy from the backward wave oscillator as depicted in FIG. 1, per conventional techniques. Since the literature is replete on the operational and design characteristics of backward wave oscillator tubes, a detailed description thereof is not deemed necessary. See, for example, Proceedings of the Institute of Radio Engineers, vol. 41, pp. 1602–1611, November 1953. See also the Proceedings of the I.R.E., vol. 43, No. 6, June 1955, pp. 684–697.

With regard to the physical and electrical parameters of the fin supported helical slow wave circuit depicted in FIGS. 1 and 2, the lowest order passband of the fundamental mode will have a high frequency cut-off when the helix or interconnected rings are approximately $\frac{1}{2}\lambda$ in circumferential length between points A and B, taken the long way around the helix circumference, where λ is the free space wavelength at the upper cut-off frequency and where the group velocity $v_g \rightarrow 0$ or expressed another way, a π radian phase shift exists between points A and B. The lower cut-off frequency for the circuit depicted in FIGS. 1 and 2 for the lowest order passband will occur when the electrical distance between points C and D is approximately $\frac{1}{2}\lambda$ (assuming propagation transverse to the Z axis) where λ is freespace wavelength at the lower cut-off frequency where the group velocity $v_g \rightarrow 0$ or to express it another way, a π radian phase shift exists between points C and D. The low frequency-cut-off conditions are similar to the low frequency cut-off conditions of the ridged waveguide of similar cross-section. A theoretical analysis can be found in any standard reference work. The high and low cut-off frequencies for higher order passbands are similarly derived.

The fin or plane supported helical slow wave circuit as depicted in FIGS. 1 and 2 has considerable advantages from a thermal standpoint over a conventional helix slow wave circuit. The supporting fin **27** can be made as wide W as desired with the limitation that the upper cut-off frequency will vary accordingly, as described above. Naturally, the thicker the dimension W of the support fin **27** is, the greater the thermal dissipation properties of the slow wave circuit are. Therefore, it is possible to increase the amount of current interception on the helix as depicted in FIGS. 1 and 2, to a much greater extent than possible in the conventional dielectric supported helix slow wave circuit without destruction of the circuit through overheating, etc. Hence greater efficiencies at higher powers are possible with the fin supported helix because the greater heat dissipation properties allow reduced spacing between helix and electron beam.

The loading ridge **28** greatly increases the absolute and useful bandwidth capabilities of the circuit without introducing extraneous modes or destroying the characteristics of the fundamental mode. Since a single fundamental mode of propagation occurs in the circuit of FIGS. 1 and 2, there is no problem of mode interference. As previously mentioned, the absolute R.F. power capacities of the fin supported helical type of slow wave circuit are superior to the simple rod supported helix circuits which are conventionally used. In addition, at millimeter wavelengths the fabrication costs of the fin supported helical slow wave circuit are obviously less than a thermally comparable stub supported helical circuit.

The slow wave circuit depicted in FIGS. 1 and 2 is defined as a fin supported helical slow wave circuit having n elongated conductive loading ridges and n elongated support fins wherein n is 1.

FIG. 3 depicts a ridge loaded fin supported helical slow wave circuit **33** which includes n elongated fin members **34, 35** and n elongated ridge members **36, 37**, wherein n is 2. Once again, a standard helix **38** made of any suitable material, such as molybdenum, copper, etc., functions as the main propagation vehicle for traveling electromagnetic wave energy in conjunction with the support fins. An annular tubular waveguide **39** surrounds the fin supported helical slow wave circuit and forms an integral part thereof as will be explained in more detail hereinafter. The presence of the loading ridges **36** and **37** at the position of highest electrical field intensity for the desired operating mode greatly enhances the absolute and useful bandwidth capabilities of the circuit without destroying the useful characteristics of the operating modes. The aforementioned bandwidth advantages result from introduction of capacitance between helix or rings and the surrounding waveguide wall which functions to both widen the absolute bandwidth while causing a reduction in change of impedance with frequency away from the upper cut-off frequency of the passband. The thermal advantages inherent in the utilization of two support fins extending along the axial extent of the helix **38** are apparent and thus a circuit capable of operating at higher efficiencies without thermal destruction thereof is achieved.

In order to better understand the nature and order of improvement in interaction impedance K at the upper end of the passband and the increase in both useful and absolute bandwidth achieved through the utilization of

loading ridges such as **28, 36, 37,** etc. reference to FIGS. 16 and 17 is made at this point.

In FIG. 16, the dashed curve labeled C is representative of the order of improvement in both absolute and useful bandwidth achieved when a loading ridge is employed in contradistinction to an identical fin supported helical slow wave circuit which does not employ a loading ridge, labeled Out-of-Phase Mode. The order of improvement is evident by the reduction in the sharpness of the drop-off in v_g from the high end of the band or upper cut-off frequency. The gradual slope of curve C allows operation over a wider band of frequencies while maintaining useful interaction impedance both from absolute and useful bandwidth viewpoints as clearly shown in FIG. 17, where K vs. f for the upper half of the band is shown both with (curve labeled B) and without (curve labeled A) the loading ridge. It is noted that useful K is obtained over a much wider band of frequencies at the upper end of the passband when a loading ridge is utilized

With regard to the physical and electrical parameters involved in a circuit wherein n is 2 such as depicted in FIG. 3, the two support fins divide the slow wave circuit into two more or less independent halves. Each half, taken by itself, will support and propagate a wave. These two halves are coupled together by their mutual volume inside the helix and in the well-known way of mutually coupled transmission lines, support two independent transmission modes, one in which the two halves are in-phase and one in which they are out-of-phase. The modes labelled according to this phase differentiaton, differ only slightly in their phase characteristics (ω–β curves). In general, a structure with n films will have 2^{n-1} such overlapping modes in each passband, in particular in the lowest order passband which has the greatest practical utility. Certain of these modes will have identical passbands, but different field configurations. Structural asymmetrics will cause these "degenerate" (identical) passbands also to separate into multiples. The high frequency cut-off for both the in-phase and out-of-phase mode in the lowest order or fundamental passband will occur approximately when the electrical length for the electromagnetic travelling wave energy is ½λ between points E and F and points G and H along the circumferential length of the helix, taken in the direction of the respective arrows, where λ is again free space wavelength at the upper cut-off frequency, where $v_g \rightarrow 0$ or agan to express it another way, a π radian phase shift exists between points E and F and G and H, respectively.

The low frequency cut-off in the fundamental passband for both the in-phase and out-of-phase modes will occur approximately when each symmetrical half, with the plane of symmetry through the fins, is an electrical ½λ wide or expressed another way $v_g \rightarrow 0$ at the low frequency cut-off and each symmetrical half is therefore resonant at the lower cut-off frequency with π phase shift between points I and J, and K and L, respectively.

Fabrication advantages, especially for millimeter wave tubes, as well as thermal advantages inherent in the fin or plane design of the present invention are also evidenced from the standpoint of enhanced Ka ratios for the fin supported helical slow wave circuit. Ka can be defined as the ratio of helix or ring circumference to wavelength of the electromagnetic wave energy in the lowest order passband. It is apparent that as n or the number of fins is increased Ka will increase for the lowest order passband in proportion to n since $Ka=2\pi r/\lambda_0$ where r equals ring or helix radius and λ_0 equals free space wavelength of the electromagnetic wave energy.

As evidenced from the above discussion, the fin supported helical type of slow wave circuit depicted in FIG. 3 has two discrete propagating modes having overlapping passbands which are arbitrarily characterized as the in-phase and out-of-phase modes. For a schematical view of these modes from a current flow pattern and E-field standpoint, for the two fin case, see FIGS. 10–13. FIG. 10 depicts a portion of the E-fields and the current flow patterns for the high frequency cut-off conditions for the out-of-phase mode. The out-of-phase mode for the fundamental passband can be excited when diametrically opposed portions of the helix or rings are excited out-of-phase and as evidenced from the current paths in this particular mode, the presence or absence of the fins has little effect thereon since the currents of this mode are not appreciably affected by the fins and because this mode is capable of existing on an isolated array of rings. FIG. 11 depicts the low frequency cut-off conditions present for this out-of-phase mode is the fundamental passband. The terminology out-of-phase, although arbitrary, can be referenced to the E-fields as denoted in FIG. 10 by dotted lines E, being oppositely directed at 180° space rotated or diametrically opposed portions of the rings. The same conditions hold for the fin supported helix, hence the generic terminology "fin supported helical slow wave circuit."

FIG. 12 depicts the in-phase mode high frequency cut-off condition which occurs for the two fin case when diametrically opposite or 180° space rotated portions of the ring or helix are excited in-phase. As evident from the current paths and E-field configurations of FIG. 12, for the high frequency cut-off condition for the fundamental passband, the presence of the fins is a necessary condition for the existence of this mode and appreciably affects the current paths and thus the in-phase mode is dependent upon the presence and nature of the fins. It is to be noted that the E-fields have the same direction or are in-phase between rings at 180° space rotated portions of the rings or helix. If n is larger than 2 the overlapping propagating modes are also distinguished by the relative phases of the sections into which the fins divide the circumference. These phase differences are always 0 or 180° and occur in all possible combinations.

FIG. 13 depicts the low frequency cut-of conditions for the in-phase mode of the fundamental passband. Therefore, after one observes the current flow patterns and E-field configurations present for the in-phase and out-of-phase modes for the n=2 or two fin case, it is apparent that mode separation and mode suppression can be achieved, as taught by the present invention, through selective slotting of the conducing fin or plane portion of the fin supported helical slow wave circuit along the axial extent of the slow wave structure. Therefore, if one selects a desired mode of operation such as the out-of-phase mode rather than the in-phase mode for n=2, then it is possible to design a fin supported helical type of slow wave circuit wherein n=2 or more, which has mode separation and mode suppression. Since the number of discrete modes having overlapping passbands is a function of the number of fins selective slotting of one or more fins is easily accomplished as taught more explicitly hereinafter in order to provide mode suppression and separation.

In FIGS. 4–7 and 9, several techniques of mode separation as well as mode suppression are taught. The techniques of mode separation and mode suppression taught herein are equally applicable to amplifiers as well as backward wave oscillators. Mode separation in backward wave oscillators utilizing fin supported helical slow wave circuits is important to the tube designer if an oscillator having predictable operating characteristics is desired.

In FIG. 14, the ω–β diagram for the lowest order passband (forward and backward wave branches) for beam-circuit interaction is shown where they are two overlapping passbands. The beam velocity curves for both forward wave and backward wave interaction are shown. Cumulative (synchronous) interaction between the beam and slow wave circuit occurs at frequencies where the beam and circuit ω–β curves cross. In FIG. 14, cumulative interaction would be present at frequencies ω_1 and ω_2 for

the backward wave case or at ω_3 and ω_4 for the forward wave case.

Amplification or oscillation will occur where cumulative interaction is present. In case there are two or more synchronous interaction points simultaneously present, oscillation or amplification is possible at any of the frequencies. If the start-oscillation current is exceeded at more than one frequency, simultaneous oscillation will not, in general, occur. Rather, discontinuous jumping from one frequency to another is apt to occur. In addition, it is obviously necessary to control which frequency is to be utilized for the output. In the case of amplification using one synchronous interaction point, reflections in the circuit in another mode may cause unwanted oscillation in that mode. In general, simultaneous synchronous interaction in more than one mode of approximately equal amplitude is dangerous to stable operation of either an oscillator or amplifier and is to be avoided.

The techniques of mode separation and suppression taught herein are aimed at removing the possibility of operation in more than one mode by significantly reducing the amplitude of one or more interfering modes so that they are no longer a threat to stable operation. The basis for this is to perturb the interfering modes while leaving the desired one essentially unchanged. The perturbations consist of geometric alterations of the circuit which change the ω–β curves of undesired modes and are applied periodically (at least 1 period P) along the structure so that the circuit in the undesired modes, has one ω–β characteristic over a portion of its length and other characteristics over other portions. Thus, synchronism between beam and wave cannot be maintained over the entire length, and the starting current for oscillations will be materially raised for these undesired modes. The perturbations are selected so that the passband of the desired mode is materially unaffected or to a degree that can be compensated for by minor changes in geometry in ways well known in the microwave art.

Since the in-phase and out-of-phase modes are dependent upon different geometrical parameters in the fin supported helical slow wave circuit as taught by the present invention, it is possible to utilize the following mode separation and suppression techniques in both amplifiers and oscillators in order to provide stable predictable operating characteristics. The circuit in FIGS. 4 and 5 is similar to the two fin circuit of FIG. 3 and similar parts are provided with similar reference numerals and a description of same will not be repeated.

In FIGS. 4–6, an elongated slot **41**, which extends over a plurality of periodic lengths P, is cut into one of the support fins **34**. The presence of this slot removes the conductive continuity between mutually opposed portions of adjacent rings or helix turns as the case may be. This slotting technique results in a radical perturbation of the in-phase mode but does not substantially upset or perturb the out-of-phase mode which is not critically dependent upon the presence of the fins as is the case for the in phase mode. Since the start oscillation current in a backward wave oscillator, as well as in an amplifier with feedback due to reflection or other sources, is dependent upon active circuit length, an effective mode suppression and mode separation tool is provided by selective slotting of the fin or fins as taught herein. It is necessary for the slot to extend over at least one period and preferably two or more periods of the circuit, in order to obtain mode separation and suppression as taught herein. The number and kind of such elongated slots will, of course, depend on the degree of mode separation and suppression desired by the designer. The slots may be staggered both in spacing from each other or may be periodically spaced from each other. The slot lengths may be staggered to span different periodic lengths or they may be made similar. Abrupt discontinuities such as **43**, **44** are preferred from a fabrication point of view for millimeter wavelength devices but do present the possibility of impedance discontinuities of sufficient magnitude being present to introduce reflection in the operating mode or out-of-phase mode and thus reduce operating efficiency.

Furthermore, such abrupt discontinuities in a high power amplifier design can, depending on slot length and beam current result in reflection oscillations occurring in either or both the in-phase mode and the out-of-phase mode due to the impedance discontinuities introduced by the abrupt edges. For example, if the number of periodic lengths P, spanned by a slot such as **41**, for a given beam current, exceeds the start oscillation current conditions for the out-of-phase mode, reflection oscillations could occur in the slotted region in the desired operation mode or out-of-phase mode. If the non-slotted region or distance between slots is made too long in the sense that the combination of operating beam current and periodic lengths between slots is sufficient to exceed the start oscillation conditions for either or both the in-phase and out-of-phase modes then reflection oscillations may occur in these sections when abrupt discontinuities are employed. Therefore, it is particularly desirable in high power amplifiers utilizing the fin supported helical type of slow wave circuit to taper the junction between slotted and non-slotted portions to avoid such undesired oscillations as well as simple reflection losses in the operating mode which will degrade efficiency. The slotted regions will also suppress backward wave oscillations in the undesired or in-phase mode to a degree which is a function of the number of periods P spanned by a given slot and the spacing between slots since the start oscillation condition for backward waves is as mentioned previously, a function of active circuit length.

The tapered version in FIG. 6, using tapered discontinuities **45**, **46** is a typical example of a useful mode separation slot **41** having tapered discontinuities.

In FIG. 7 a fin supported slow wave circuit having two fins **51**, **52** and two loading ridges **53**, **54** in conjunction with a ring type of fin supported helical slow wave circuit **55** is depicted in perspective. The fin supported helical slow wave circuit **55** includes conductive support fins **51**, **52** and a plurality of rings **56**, brazed or the like to the fins at diametrically opposite sides and extending along the axial length of the circuit and coaxially disposed about the central beam axis Z. A conductive circular waveguide **57** which forms part of the vacuum envelope as well as functioning as a thermal heat sink in conjunction with support fins **53**, **54** completes the slow wave circuit.

In FIG. 7, another form of physical perturbation is depicted. Herein the elongated slots **58** do not interrupt the conductive continuity between mutually opposed portions of adjacent rings or between mutually opposed portions of adjacent turns of a helix, but do extend over a number of periods (periodic lengths) P of the slow wave circuit and perturb current flow between rings or helix and the surrounding waveguide. After consideration of the current flow patterns and E-field configurations shown in FIGS. 11 and 13, it is evident that the low frequency cut-off of the in-phase mode is greatly lowered because the current of FIG. 13 is required to flow around the slot while the low frequency cut-off of the out-of-phase mode is little perturbed since the current of FIG. 11 need not flow around the slot but may flow through the slot into the adjacent waveguide current system.

The same considerations discussed previously in conjunction with tapered discontinuities between slotted and non-slotted portions with regard to minimizing undesired reflection oscillations and reflected energy in the slots in amplifier traveling wave tubes are applicable to the slotted version depicted in FIG. 7. The slots **58** in fin **51** of the embodiment of FIG. 7 differ functionally from the slots depicted in FIGS. 4–6 in the following manner. The slots **41** interrupt the current paths between adjacent rings or helix turns over a plurality of periodic lengths and thus the in-phase mode is radically perturbed along the slotted portion **41** which results in distinct separation between

in-phase and out-of-phase modes as evidenced in FIG. 16. On the other hand, slots **58** perturb the low frequency cut-off currents of the in-phase mode thus lowering this mode.

For a better understanding of the mode separation properties of both types of slots **41** and **58** as well as transformations therebetween reference to FIGS. 14–16 is now made. FIGS. 14–16 are illustrative ω–β diagrams depicting the relationship between the in-phase and out-of-phase modes in the fundamental passband for the non-slotted condition depicted in FIG. 3 and for the slotted regions of FIGS. 7 and 4, respectively. Examination of the passband characteristics in FIG. 14 for the lowest order passband for the non-slotted dual fin supported helical slow wave circuit shows the in-phase and out-of-phase modes to have propagating characteristics which result in overlapping passbands. The effect of selective slotting of one of the conducting support fins over a plurality of consecutive periods P in the case shown in FIG. 4 is depicted in FIG. 16. It is to be noted that the high frequency cut-off is substantially affected for the in-phase mode and not substantially affected for the out-of-phase mode for this type of perturbation, while the low frequency cut-off for the in-phase mode is substantially lowered and little change in the low frequency cut-off for the out-of-phase mode occurs. Therefore, distinct mode separation occurs.

In FIG. 15, it is seen that when slots such as depicted in FIG. 7 are utilized a substantial change occurs in the low frequency cut-off conditions for the in-phase mode. The low frequency cut-off for the in-phase mode is lowered in much the same fashion as set forth in connection with FIG. 16 while the high frequency cut-off for the in-phase mode is not appreciably perturbed. Similarly, the high frequency cut-off for the out-of-phase mode is not affected and the low frequency cut-off for the out-of-phase mode is only slightly lowered. Thus, it is seen that indeed worthwhile mode perturbation is achiever utilizing the selective slotting techniques of the present invention.

In FIG. 9 a fin supported helical slow wave circuit is depicted which incorporates for the purpose of illustration a combination of slots such as depicted in FIGS. 4 and 7. The slow wave circuit of FIG. 9 employs axially spaced rings **62** supported on a pair of 180° space rotated axially co-extensive fins **63**, **64**. A cylindrical waveguide **65** surrounds the fin supported helical slow wave circuit and is conductively or D.C. shorted thereto as in the previous embodiments.

Three different types of slots are depicted in FIG. 9 for illustrative purposes, namely, slots **67**, **68** and **69**. Slots of the type denoted by **67** and **68** and their individual mode separation properties have been discussed previously. Slot **69** simply represents an intermediate physical transformation between the extremes represented by **67** and **68** but electrically is more nearly like slot **68**. For example, a slot, such as **69** will not appreciably perturb the high frequency cut-off of the out-of-phase mode nor the in-phase mode. It will, however, appreciably perturb the low frequency cut-off for the in-phase, but not the out-of-phase mode.

The mode suppression control aspects of the slots are a function of the number of periods over which they exist. Complete suppression of unwanted oscillations in both amplifiers and oscillators can be obtained by making the number of periods spanned by any one slot or the spacing between slots less than the circuit length required for the start oscillation conditions for a given beam current for the type of oscillation being considered. Tapered transitions will minimize the danger of reflection oscillations occurring in the desired mode. The combination of mode suppression and mode separation provides the tube designer with extremely simple stability control techniques for both oscillator and amplifier traveling wave tubes. In other words, by properly combining the aforementioned mode control techniques it is possible to optimize both thermal and stability characteristics for a traveling wave tube regardless of whether it is to function as an amplifier or an oscillator for any given set of design constraints.

In FIG. 8 a fin supported helical slow wave circuit **70** utilizing two loading ridges **71**, **72** diametrically opposite each other and 90° phase rotated with respect to the conductive support fin **73** is depicted. This configuration finds particular utilization in a traveling wave amplifier operating in a higher order passband. The utilization of the two loading ridges **71**, **72**, 90° space rotated with respect to the support fin **73**, serves to increase the fixed voltage bandwidth of the first higher order passband. The loading ridges are positioned at points of high field intensity for forward wave first higher order passband bode of propagation and utilizing the same reasoning as applied to the ridge loading techniques employed in conjunction with FIGS. 2 and 3 as explained in FIGS. 16 and 17 a similar improvement is achieved. A helix **74** serves as a main propagating vehicle in the embodiment depicted in FIG. 8. It is to be noted that spaced rings may be substituted therefor, as in the previous embodiments. A conductive circular waveguide **75** is coaxially disposed about the beam axis Z and conductively of D.C. shorted to the ridges and fin as in the previous embodiments. The high frequency cut-off of the embodiment in FIG. 8 operating in the first higher order passband will occur when the electrical length between points N and M as measured around the ring circumference approximates λ and the low frequency cut-off for the first higher order passband will occur when a 2π radian phase shift exists between points R and S, or to express it another way, the electrical distance between points R and S is λ (assuming propagation transverse to the Z axis) where λ is the free space wavelength at the lower cut-off frequency where $v_g \rightarrow 0$.

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 slow wave circuit adapted and arranged for supporting electromagnetic traveling wave energy thereon, said slow wave circuit including, a fin supported helical slow wave circuit disposed along and defining an elongated central axis, said fin supported helical slow wave circuit including *n* elongated fin support members and being mounted and supported along the axial extent thereof, on and by, respectively, said *n* elongated fin support members, the longitudinal axis of each of said *n* elongated fin support members being substantially parallel to and spaced from said central axis along the axial extent of said fin supported helical slow wave circuit, at least one of said *n* elongated fin support members is provided with at least one slotted portion, said slotted portion extending over at least two consecutive periods of said fin supported helical slow wave circuit, said slow wave circuit having *n* elongated conductive loading ridges extending along the axial extent of said fin supported helical slow wave circuit, each of said *n* elongated conductive loading ridges being geometrically spaced from said fin supported helical slow wave circuit along the axial extent of said fin supported helical slow wave circuit, and wherein *n* is selected from one of the following integers 1, 2, 3, 4, 5, 6, 7, or 8.

2. The slow wave circuit defined in claim **1** wherein the transition between said slotted portion and said non-slotted portion on said slotted fin support member includes an abrupt discontinuity.

3. The slow wave circuit defined in claim **1** wherein the transition between said slotted portion and said non-slotted portion on said slotted fin support member includes a tapered section.

4. The slow wave circuit defined in claim **1** wherein said slotted portion is adapted and arranged to provide a

physical spacing between said slotted fin support member and mutually opposed portions of adjacent turns of said fin supported helical slow wave circuit over said at least two consecutive periods.

5. A slow wave circuit adapted and arranged for supporting electromagnetic traveling wave energy thereon, said slow wave circuit including, a fin supported helical slow wave circuit disposed along and defining an elongated central axis, said fin supported slow wave circuit including *n* elongated fin support members and being supported along the axial extent thereof by said *n* elongated fin support members, the longitudinal axis of each of said *n* elongated fin support members being substantially parallel to and spaced from said central axis along the axial extent of said fin supported helical slow wave circuit, at least one of said *n* elongated fin support members being provided with at least one slotted portion, said slotted portion extending over at least two consecutive periods of said fin supported helical slow wave circuit and wherein *n* is selected from one of the following integers 2, 3, 4, 5, 6, 7, or 8.

6. The slow wave circuit defined in claim 5 wherein at least one of said *n* elongated fin support members is provided with a plurality of axially spaced slotted portions, each of said plurality of slotted portions extending over at least two consecutive periods of said fin supported helical slow wave circuit.

7. The slow wave circuit defined in claim 5 wherein the transition between said slotted portion and said non-slotted portion on said slotted fin support member includes an abrupt discontinuity.

8. The slow wave circuit defined in claim 5 wherein the transition between said slotted portion and said non-slotted portion on said slotted fin support member includes a tapered section.

9. The slow wave circuit defined in claim 5 wherein said fin supported helical slow wave circuit including said *n* elongated fin support members is disposed within and

conductively interconnected within a conductive waveguide.

10. The slow wave circuit defined in claim 5 wherein said at least one slotted portion is adapted and arranged to provide a physical spacing between said slotted fin support member and mutually opposed portions of adjacent turns of said fin supported helical slow wave circuit over said at least two consecutive periods.

11. A high frequency electron discharge device of the traveling wave type including an electron gun disposed at the upstream end portion thereof, a collector disposed at the downstream end portion thereof and a slow wave circuit disposed therebetween, said slow wave circuit including a fin supported helical slow wave circuit disposed along and defining an elongated central axis, said fin supported helical slow wave circuit having *n* elongated fin support members and being supported along the axial extent thereof by said *n* elongated fin support members, the longitudinal axis of each of said *n* elongated fin support members being substantially parallel to and spaced from said central axis along the axial extent of said fin supported helical slow wave circuit, at least one of said *n* elongated fin support members being provided with at least one slotted portion, said slotted portion extending over at least two consecutive periods of said fin supported helical slow wave circuit and wherein *n* is selected from one of the following integers 2, 3, 4, 5, 6, 7 or 8.

References Cited

UNITED STATES PATENTS

2,885,641	5/1959	Birdsall et al.	333—31
2,942,143	6/1960	Epsztein	315—3.5
3,102,969	9/1963	Arnaud	315—31 X

ELI LIEBERMAN, *Primary Examiner.*

PAUL L. GENSLER, *Assistant Examiner.*