Sept. 9, 1958 C. K. BIRDSALL 2,851,630

HIGH POWER TRAVELING-WAVE TUBE

Filed April 13, 1955 2 Sheets-Sheet 1

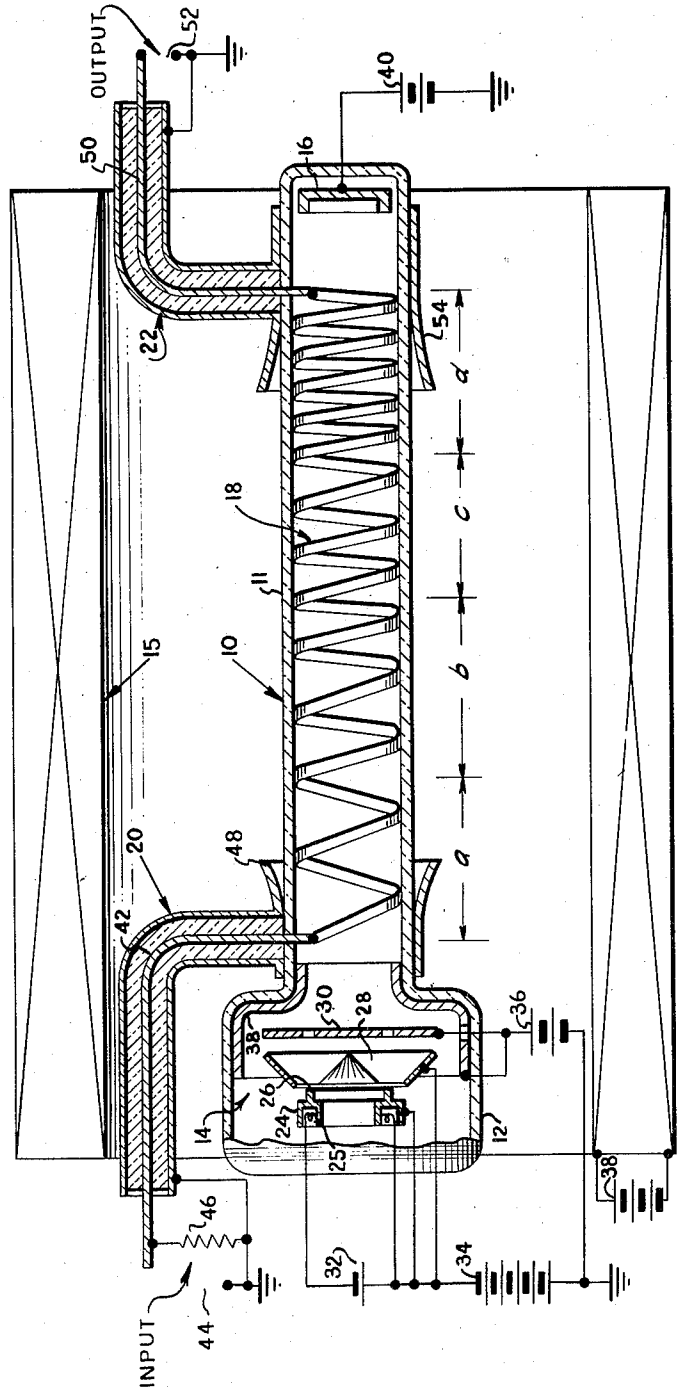

FIG. 1

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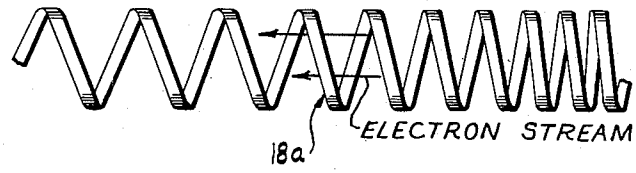


FIG. 2

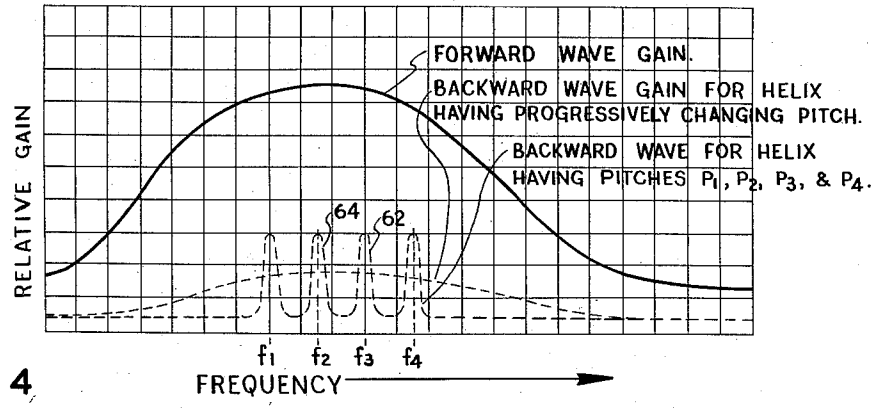
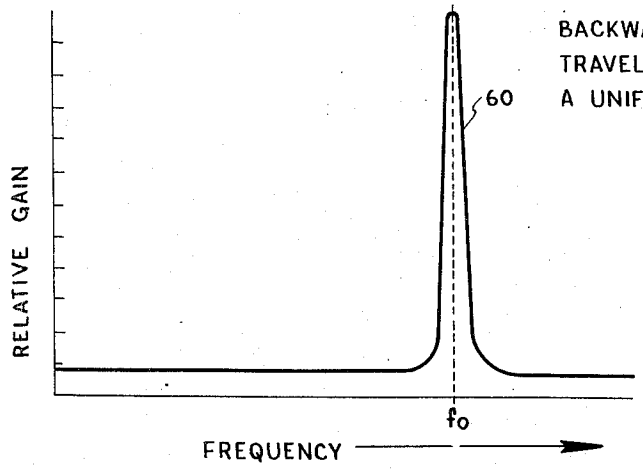


FIG. 4



BACKWARD WAVE GAIN OF A TRAVELING WAVE TUBE HAVING A UNIFORM PITCH HELIX.

FIG. 3

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HIGH POWER TRAVELING-WAVE TUBE

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Application April 13, 1955, Serial No. 501,212

5 Claims. (Cl. 315—3.5)

This invention relates to high power microwave tubes and more particularly to a traveling-wave tube incorporating a large diameter helical slow-wave structure which possesses characteristics that greatly increase the "start-oscillation" current for backward-wave oscillations.

As is presently known, it is advantageous in a traveling-wave tube incorporating a helix to have a helix circumference of the order of a half wavelength at the operating frequency of the device in order to achieve very high power outputs at the higher frequencies. Helices this large allow very large beam currents to be employed at practical current densities. A tube with a large diameter helix is disclosed in a copending application for patent Serial No. 401,303, entitled "Traveling-Wave Tube" filed by Dean A. Watkins and Horace R. Johnson, on December 30, 1953. In this type of tube, however, it is necessary to provide means for preventing the device from commencing backward-wave oscillations, i. e., to increase the start-oscillation current for backward-wave oscillations.

It has been found that slight variations in the pitch of the helix in a tube of the aforementioned type may have little or no effect on its forward-wave gain characteristics but may have a very pronounced effect on the start-oscillation current for backward-wave oscillations. By way of example, a slight change in the pitch of the turns for one-half the length of a large diameter helix with respect to the pitch of the turns of the remaining half may increase the start-oscillation current by approximately 8 times that of a helix having a uniform pitch along its entire length. It is thus apparent that with the pitch change, the beam current employed for forward-wave amplification in such a device may be substantially increased without having backward-wave oscillations commence, as would have been the case with uniform pitch.

In accordance with the present invention, a high power traveling-wave tube is provided that incorporates a periodic slow-wave structure such as, for example, a large diameter helix, which has a plurality of sections of different pitch. Alternatively, in order to avoid reflections due to the abrupt changes in pitch, a slow-wave structure such as a large diameter helix, having either a progressively increasing or decreasing pitch is employed. In this manner, the start-oscillation current for backward-wave oscillations is increased to the extent that the device may be used effectively as a forward wave amplifier without other means of preventing the backward-wave oscillations.

It is therefore an object of this invention to provide an improved high power traveling-wave amplifier tube.

Another object of this invention is to provide a traveling-wave amplifier tube incorporating a helical slow-wave structure requiring substantially more current to commence backward-wave oscillations than in conventional structures of this type.

Still another object of this invention is to provide a traveling-wave tube incorporating a helical slow-wave structure constituted of a plurality of sections having different pitch to prevent backward-wave oscillations from commencing.

A further object of this invention is to provide a traveling-wave tube incorporating a helical slow-wave structure having either a progressively increasing or decreasing pitch to prevent backward-wave oscillations from commencing.

The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawings in which several embodiments of the invention are illustrated by way of example. It is to be expressly understood, however, that the drawings, are for the purpose of illustration and description only, and are not intended as a definition of the limits of the invention.

Fig. 1 is a diagrammatic sectional view in partial elevation of an embodiment of the invention together with associated circuitry;

Fig. 2 is an elevational view of an alternate embodiment of the helical slow-wave structure of the present invention; and

Figs. 3 and 4 are illustrative diagrams of gain versus frequency.

Referring now to the drawings, Fig. 1 illustrates an embodiment of the present invention comprising an evacuated envelope **10** which consists of a long cylindrical portion **11** and an enlarged portion **12** at the left extremity, as viewed in the drawing. Enlarged portion **12** houses an electron gun **14** which produces a hollow cylindrical electron stream. This electron stream is directed concentrically through the long cylindrical portion **11** to the opposite extremity thereof by a solenoid **15** where it is intercepted and collected by a collector electrode **16**. In accordance with a preferred embodiment of the invention, a helical slow-wave structure **18** having a non-uniform pitch and provided with coaxial input and output cables **20** and **22**, respectively, is disposed contiguously along the path of the electron stream intermediate the electron gun **14** and the collector electrode **16**.

More particularly, electron gun **14** comprises an annular cathode **24** with a heater **25** and an electron emitting surface **26**, a focusing electrode **28**, and an accelerating electrode **30**, the electrodes **28** and **30** being provided with apertures in register with the electron emitting surface **26** of cathode **24** to allow passage therethrough of the hollow cylindrical electron stream. The electron emitting surface **26** is energized by means of a battery **32** connected across the heater **25**, one terminal of which may be connected to the cathode **24**, as shown. The focusing electrode **28** provides an inner and an outer surface of revolution adjacent to and about the electron emitting surface **26** of cathode **24** at an angle of approximately 67.5° with the longitudinal axis of the helix **18**, as shown in the drawing. Cathode **24** and focusing electrode **28** are connected together and are maintained at a potential of the order of 3000 volts negative with respect to ground by means of a connection therefrom to the negative terminal of a battery **34**, the positive terminal of which is connected to ground.

Accelerating electrode **30** is disposed in a plane normal to the longitudinal axis of helix **18** and to the right of focusing electrode **28**, as viewed in the drawing. Electrode **30** is maintained at a potential that is of the order of 200 volts positive with respect to ground by means of appropriate connections to a battery **36**. An equipotential region is provided between the electron gun **14** and the helix **18** by means of a conductive coating **38** disposed about the inner periphery of the envelope **10** intermediate the focusing electrode **28** and the helix **18**. This

equipotential region is maintained at the same potential as the accelerating electrode **30** by means of a connection to the battery **36**.

The hollow electron stream thus produced by electron gun **14** is directed concentrically through the helix **18** by means of the solenoid **15** which is disposed concentrically about the envelope **10** and is coextensive therewith. An appropriate direct current is made to flow through the solenoid **15** to produce an axial magnetic field of the order of 600 gauss to constrain the electron stream throughout the active length of the tube. The solenoid **15** is thus energized by means of connections across a battery **38**. The collector electrode **16**, disposed so as to intercept the electron stream at the right extremity of envelope **10**, as viewed in the drawing, is maintained at a potential more positive than that of helix **18** to suppress secondary electron emission. In the present case, this is accomplished by maintaining collector electrode **16** at a potential of the order of 50 volts positive with respect to ground by means of appropriate connections to a battery **40**.

Disposed intermediate the electron gun **14** and the collector electrode **16** is the helical slow-wave structure **18**. An electromagnetic signal wave is launched on the helix **18** by means of the input coaxial section **20**. Coaxial section **20** has a center conductor **42** which connects the high side of input terminals **44** directly to the first turn of helix **18** nearest the electron gun **14**. A resistor **46** is interconnected between the center conductor **42** of coaxial section **20** and ground in order to maintain the helix **18** at quiescent ground potential. The outer conductor of coaxial section **20** is connected to a ferrule **48** which is disposed concentrically about the first several turns of the helix **18** on the outside of the envelope **10**. The extremity of ferrule **48** away from electron gun **14** is flared out in order to improve the impedance match between coaxial section **20** and helix **18**. The outer conductor of coaxial section **20** and ferrule **48** may be maintained at any substantially fixed direct-current potential such as, for example, at ground by means of a connection thereto.

The output from the device of the present invention is provided by the output coaxial section **22**. Section **22** has a center conductor **50** which interconects the last turn of helix **18** farthest from the electron gun **14** to the high side of output terminals **52**. In addition, a matching ferrule **54** is disposed concentrically about the last several turns of helix **18** and connected to the outer conductor of coaxial section **22** which is, in turn, connected to ground in the same manner as is that of the input coaxial section **20**.

As previously specified, the helical slow-wave structure **18** is of the type that has a large circumference as compared to a free space wavelength at its operating frequency, such as, for example, 0.2 to one-half a free space wavelength. The inner diameter of the helical structure **18**, on the other hand, is preferably of the order of 1.4 times the diameter of the hollow cylindrical electron stream produced by electron gun **14**. In accordance with a first embodiment of the invention, the length of helical structure **18** is constituted of a plurality of portions, each of which has a different pitch. As shown in Fig. 1, for example, the portions *a*, *b*, *c*, and *d* of the helical structure **18** have pitches of p_1, p_2, p_3, and p_4 turns per inch, respectively. Alternatively, the pitch of the helical structure may be, in accordance with a second embodiment of the invention, made to progressively increase or decrease as represented by the helix **18***a*, shown in Fig. 2. The helix **18** or **18***a* may be reversed, end for end, with respect to the direction of the electron stream, in which case the helix pitch would increase or decrease, respectively.

In operation, the helical slow-wave structures **18** or **18***a* substantially decrease the current at which backward-wave oscillations commence by distributing the backward-wave gain over several frequencies or uniformly throughout the portion of the frequency spectrum where the tube is operated. For example, a typical backward-wave gain versus frequency characteristic **60** for a traveling-wave tube incorporating a helix having a uniform pitch is illustrated in Fig. 3. Referring to this figure, it is seen that the gain of a conventional tube increases sharply at the frequency, f_0. This frequency, f_0, is dependent upon the circumference and pitch of the helix and the velocity of the electron stream. It is thus apparent that, with a gain of this magnitude at the frequency f_0, there would be a tendency for the tube to commence backward-wave oscillations as it only remains to satisfy the phase requirements for oscillation about the incremental feedback loop along the helix when the total gain about the equilavent feedback path is greater than unity.

However, it is possible to satisfy the conditions for backward-wave oscillations for only a portion of the length of the slow-wave structure. Hence, the backward-wave attenuation for a particular frequency over the remaining portion of its length cannot be relied upon to prevent backward-wave oscillations. Referring to Fig. 4, there are illustrated the gain characteristics for a constant velocity electron stream of the helix **18** having pitches p_1, p_2, p_3, and p_4 and helix **18***a* having a progressively increasing or decreasing pitch, represented by dashed lines **62**, **64**, respectively. The gain characteristic **62** of helix **18**, for example, has backward-wave gain at frequencies f_1, f_2,f_3, and f_4 which correspond, respectively, to the pitches p_1, p_2, p_3, and p_4. The gain at any of the frequencies f_1, f_2, f_3, and f_4 may be of the order of 1/64 that of a single helix having a single uniform pitch. Also, the gain characteristic **64** of the helix **18***a* extends over a comparatively broad portion of the frequency spectrum and may be of the order of 1/20 that of a single uniform pitch helix, depending on the extent of the increase or decrease of pitch over the length of the helix. The forward wave gain, on the other hand, as represented by line **66** of Fig. 4, extends over a broad range of frequencies and is not substantially affected by the different pitches p_1, p_2, p_3, and p_4 of helix **18** or the progressively increasing or decreasing pitch of helix **18***a*. Thus, it is seen that the helices **18** or **18***a* of the present invention may be employed as the slow-wave structure in a traveling-wave amplifier tube to substantially decrease the start-oscillation current for backward-wave oscillations.

More particularly, it may be shown that the conditions for backward-wave oscillations for a uniform pitch or periodic structure are met when the following relation exists:

$$CN \geqslant 0.314 \qquad (1)$$

wherein

C is the Pierce gain parameter of the device, and
N is the total length of the uniform pitch or periodic slow-wave structure in wavelengths.

The Pierce gain parameter, C, however, is proportional to the one-third power of the beam current, i. e.

$$C \simeq I^{1/3} \qquad (2)$$

wherein I is the current represented by the electron beam produced by electron gun **14**. It is thus apparent that if I_0 be designated as the start-oscillation current, i. e., the current at which backward-wave oscillations commence, then

$$I_0^{1/3}N = \text{constant} \qquad (3)$$

As previously explained, the backward-wave gain necessary for the commencement of backward-wave oscillations occurs for only a very narrow portion of the frequency spectrum. For example, a backward-wave amplifier incorporating a uniform pitch helix has a "Q" of the order of 500. Therefore, the width, Δf, of the portion of the frequency spectrum for which gain is provided is of the order of $f_0/500$. It is thus evident that the conditions for the commencement of backward-wave oscillations must be satisfied for each portion of the length of the slow-wave structure having a different pitch. Therefore, in accord-

ance with the device of the present invention, the length of the slow-wave structure is divided into n portions, preferably of equal length, having different pitches. In this case, the Relation 3 for the commencement of backward-wave oscillations becomes

$$I_n^{1/3}\left(\frac{N}{n}\right)=\text{constant} \quad (4)$$

and from the ratio of Relations 3 and 4

$$I_n=n^3 I_0 \quad (5)$$

wherein I_n is the start-oscillation current for n sections of different pitch.

From Relation 5 it is seen that the start-oscillation current for n sections (n=2, 3, 4, and 5,) is as follows:

$$I_2=8I_0$$
$$I_3=27I_0$$
$$I_5=64I_0$$
$$I_4=125I_0$$

An additional consideration is the extent of the allowable variation between the pitches p_1, p_2, p_3, and p_4. In order to ascertain the maximum allowable variation in pitch, consideration must be given to the forward-wave gain characteristics of the device. In general, it can be shown that the forward-wave gain is down 3 decibels from its maximum where the ratio of the greatest to the smallest velocity by which the slow-wave structure propagates an electromagnetic wave is approximately equal to the quantity $(1+2C)$ where, as before, C is the Pierce gain parameter. In the case of the helices **18** and **18***a*, the velocity at which an electromagnetic wave is propagated is directly proportional to the pitch. Thus

$$\frac{p \text{ largest}}{p \text{ smallest}} \leq (1+2C) \quad (6)$$

In the case of a high power traveling-wave amplifier tube, a typical value of C is 0.1 or larger. Hence the ratio of the largest to the smallest pitch should be equal to or less than 1.1.

On the other hand, in order to determine the closeness with which the pitch of two different portions of the slow-wave structure may differ, it is necessary to consider the variation of frequency with pitch. It may be shown that a 1% pitch variation is sufficient to shift the frequency, f_0, at which maximum gain occurs by at least 1%. In that the width of the portion of the frequency spectrum amplified is only of the order of 0.2%, it is evident that a 1% change in frequency and hence pitch is more than adequate. Thus, from the foregoing it may be stated that the ratio of the pitch for any section of the slow-wave structure to the smallest pitch should be within the range from 1.01 to 1.10. It is, of course, desirable to make the changes in pitch as small as practicable and still satisfy the above relation so as to effect maximum forward wave gain and in addition make the changes occur over a transition region so as to minimize reflections.

What is claimed is:

1. A traveling-wave amplifier tube comprising a helical slow-wave structure having a plurality of different pitches and a circumference per turn of not less than 0.2 free space wavelength at the mid-frequency of operation of the tube, means for launching an electromagnetic signal wave along said helical slow-wave structure, means for producing a hollow, cylindrical electron stream having a cross-sectional area that is small compared to the cross-sectional area of said helical slow-wave structure, and means for directing said electron stream contiguously along said helical slow-wave structure at a velocity to amplify said signal wave, whereby said different pitches of said helical slow-wave structure substantially decrease the maxium overall backward-wave gain of said tube to minimize backward-wave oscillations, the inner diameter of said slow-wave structure being of the order of 1.4 times the diameter of said electron stream.

2. The traveling-wave amplifier tube as defined in claim 1 wherein said plurality of different pitches of said helical slow-wave structure is provided by a progressively increasing pitch in the direction of electron flow along said electron stream.

3. The traveling-wave amplifier tube as defined in claim 1 wherein said plurality of different pitches of said helical slow-wave structure is provided by a progressively decreasing pitch in the direction of electron flow along said electron stream.

4. The traveling-wave amplifier tube as defined in claim 1 wherein said plurality of different pitches of said helical slow-wave structure is provided by several portions of the length of said structure, each having a different uniform pitch.

5. The traveling-wave amplifier tube as defined in claim 4 wherein the ratios of the pitches of said portions to the minimum pitch thereof is from 1.01 to 1.1.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 2,851,630

September 9, 1958

Charles K. Birdsall

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

Column 4, line 32, for "1/20" read -- 1/120 --.

Signed and sealed this 18th day of November 1958.

(SEAL)

Attest:
KARL H. AXLINE

Attesting Officer

ROBERT C. WATSON
Commissioner of Patents