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TRAVELING WAVE TUBE

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This invention relates to electron discharge devices and more particularly to such devices of the traveling wave tube type which employ interdigital wave guiding structures as the wave interaction circuits.

In traveling wave tubes, an electron stream is projected past a wave interaction circuit along which is propagating an electromagnetic wave at a velocity such that cumulative interaction results between the electron stream and the electromagnetic wave whereby amplification is provided to the electromagnetic wave. There have been devised hitherto traveling wave tubes suitable for operation in the millimeter wavelength region, but such tubes generally either have had less frequency range or lower efficiencies or have been more difficult to construct than is desirable.

Accordingly, objects of the present invention are to increase the frequency range of operation, improve the efficiency, and facilitate the construction of traveling wave tubes suitable for operation at extremely short wavelengths, such as in the millimeter wavelength region.

Another object is to extend the frequency range of traveling wave tubes into still shorter wavelength regions.

To this end, a principal feature of the invention is an interdigital wave guiding structure which includes a hollow wave guiding member having as "finger" elements a longitudinal linear array of spaced wire loops extending into the hollow of the member, alternate loops being connected to the same surface of the member and adjacent loops being connected to opposite surfaces of the member in an interdigital pattern. In a preferred embodiment of the invention, each of the wire loops is "hairpin" or U-shaped having both its ends connected to the hollow wave guiding member, and an electron stream is projected longitudinally through a region of overlap of adjacent loops.

The use of interdigital wave guiding structures as wave transmission circuits in traveling wave tubes has been known hitherto but such previously known structures have not been especially suitable for operation at extremely short wavelengths, such as in the millimeter wavelength region. Such prior art structures have generally included, as finger elements, arrays of stubs or vanes extending into the hollow of a wave guiding member and usually formed as integral portions thereof. Since the dimensions of the finger elements are advantageously of the order of a quarter of the operating wavelength or less, such prior art structures for millimeter wave operation are extremely difficult to construct. On the other hand, the construction of interdigital wave guide structures utilizing wire loops as finger elements in accordance with the invention lends itself readily to grid winding techniques and, accordingly, such structures can be easily constructed. By way of example, there will be described hereinafter a process for constructing an interdigital structure of wire loop elements suitable for tubes adapted to operate at a center band wavelength of 6 millimeters. Moreover, these same techniques can similarly be applied to the construction of wave guiding structures for tubes

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for operation at still shorter wavelengths. Since it is generally desirable in interdigital structures of this kind to limit the length of the finger elements to less than a quarter of the operating wavelength in the wave guiding structure, it can be appreciated that the construction of prior art interdigital structures for tubes for use at comparable wavelengths would pose an almost insurmountable problem, particularly if it were sought to provide tubes of reproducible characteristics. The term "length of the finger elements" as used herein refers to the height of the U-shaped finger elements rather than the distance around said elements. Additionally, an interdigital circuit in accordance with the invention can be operated at considerably higher efficiencies than comparable prior art structures since the loop construction facilitates access of the electron stream for travel past the regions of high electric field. This factor is of particular importance at the extremely short wavelengths where the relatively small dimensions of the tube construction make high gain difficult of attainment.

Moreover, although the invention will be described with specific reference to embodiments in which finger elements are U-shaped wire loops for use at millimeter wavelengths, for longer wavelengths the finger elements may be U-shaped tubing through which can be circulated a cooling fluid for operation at high power levels.

The use of interdigital-type wave circuits is of special importance in tubes to be used in spatial harmonic type operation, where the electron beam is in synchronism with a spatial harmonic component of the traveling wave which is propagating with a much slower phase velocity than the fundamental component of the traveling wave. In a preferred embodiment of the invention to be described below, an interdigital wave circuit utilizing hairpin or U-shaped wire fingers is incorporated in a backward wave oscillator in which an electron stream is in synchronism with a forward-traveling spatial harmonic of a wave whose fundamental component is propagating in a backward-traveling direction (i.e. a direction opposite to that of the electron stream).

The invention will be better understood from the following more detailed description taken in conjunction with the accompanying drawings in which:

Fig. 1 shows schematically a longitudinal cross section of a backward wave oscillator as an illustrative embodiment of the invention;

Fig. 2 shows a transverse cross section taken along the lines 2—2 of Fig. 1; and

Fig. 3 shows schematically in longitudinal cross section an amplifier suitable for operation either in a forward or backward wave mode as an alternative embodiment of the invention.

For the sake of simplicity, the several embodiments have been shown schematically with many of the structural details such as supports and spacers omitted.

With reference now to the drawings, Figs. 1 and 2 show a backward wave oscillator which is enclosed by an evacuated glass envelope 10. At opposite ends of the envelope are positioned an electron gun 11 and a collector electrode 12 in target relationship. The electron gun 11 is of standard design and comprises essentially a cathode 13, a beam focussing and intensity control electrode 14, and an accelerating anode 15. The collector 12 comprises a cup-shaped element with its open end facing the electron gun. Interposed between the electron gun and the collector is the structure 16, of a non-magnetic metal such as copper, and comprising an output section 17 and an elongated interaction section 18. The interaction section 18 has a hollow interior, preferably of rectangular cross section, which serves as a wave guiding passage 19 therethrough. The cross-sectional dimensions of the passage 19 decrease gradually from maxima at the electron

source end to smaller values which are uniform along the major portion of its length. This hollow interior is aligned with the path of electron flow between the electron gun and the collector electrode and the structure 16 is provided with suitable apertures 20 and 21 at opposite ends for traversal of the electron flow axially there-through. For backward wave oscillator applications, the collector or downstream end of the passage is closed off except for the aperture 21. Throughout the specification and the claims, the term "downstream" is used to denote a point or location closer to the collector than the point or location with which it is being compared. Conversely, the term "upstream" denotes a point or location closer to the gun than the point with which it is being compared. In order to make this end substantially reflectionless over a broad band of wavelengths, in the passage there is inserted a tapered block or wedge 22 of dielectric with its tapered face 23 coated with lossy material such as powdered graphite. This wedge substantially fills the wave guiding passage and is apertured for passage of the electron flow. At the electron source or upstream end, the wave guiding passage 19 merges into a wave guiding passage 24 formed as the interior of output section 17 of the structure 16. This wave guiding passage 24 similarly is of rectangular cross section for matching the cross section of the wave guiding passage 19 at the point of merger. For convenience in leading off the abstracted energy, a conventional right angle bend 25 is provided between the wave guiding passages 19 and 24. Additionally a hollow wave guide 26 of rectangular cross section and suitably fitted to the output section 17 forms a continuation of the wave guiding passage 24 to the wall of the glass envelope 10 where it is capacitively coupled to an external wave guiding connection 36 by means of which oscillatory energy can be led off for utilization.

The useful interaction between the electron flow and the traveling wave is secured along the constricted portion of the wave guiding passage 19. For providing components having a velocity substantially equal to that of electron flow, and considerably slower than the velocity of light there is formed along this portion an interdigital structure filter-type circuit of the kind which is a principal feature of the invention. This circuit comprises, as finger elements, a linear array or succession of wire loops 31, having a hairpin or U-shaped configuration. The linear array includes two sets or rows 32 and 33, each of the rows including a series of uniformly spaced elements 31 extending inwardly from one of two opposite side wall surfaces of the wave guiding passage 19. The two rows are interleaved in an interdigital pattern so that alternate elements of the linear array extend from the same one of the two opposite side walls, while adjacent elements extend from opposite side walls. The lengths of the elements are adjusted to be more than half of the spacing between the opposite surfaces so that a region 34 of overlapping exists as shown by the transverse view of Fig. 2. The various tube elements are advantageously arranged so that the electron stream flows through this region of overlapping. In particular, it is advantageous to employ a cylindrical electron stream of circular cross section which is adjusted to be enclosed substantially completely within this region 34. Suitable stream collimating means, such as an externally positioned solenoid 35 to furnish a longitudinal magnetic field, serves to keep the electron flow straight. Cylindrical electron streams of circular cross section are well adapted for Brillouin-type electron flow with its consequent economy and simplicity in magnetic focussing. An important advantage of this form of interdigital circuit is this ready adaptability to Brillouin-type flow, of whose principles a description can be found in the copending application Serial No. 168,202, filed June 15, 1950, by C. C. Cutler.

Moreover, it is generally advantageous to provide a uniform transition between the loaded portion of the wave guiding passage 19 along which extends the inter-

digital circuit and the unloaded portion thereof. To this end, the length of the finger elements 31 decreases gradually from a uniform maximum along the major portion of the constricted passage to a minimum at the upstream end of the passage to effect a gradual reduction in the loading. This region of tapered loading acts primarily as a transformer section rather than as a portion of the interaction circuit since generally therealong there will not be components having an axial velocity sufficiently slow for stream interaction.

It also will generally be advantageous to employ finger lengths for the interaction circuit shorter than a quarter of the guide wavelength of the desired oscillatory frequency because at frequencies at which the fingers are a quarter wavelength they form a series of resonators and the propagating properties of the circuit are thereby adversely affected. However, it is possible to achieve satisfactory operation in the frequency band at which the length of the finger elements is between successive odd numbers of quarter guide wavelengths in this band.

It is characteristic of this interdigital circuit that the normal electric mode of waves propagating in the passage 19 will be distorted by the finger elements and axial electric field components will exist between adjacent elements having a strong spatial harmonic component with a fundamental periodicity given by the spacing between successive elements of one set. Electrons moving axially and close to the elements will move in a substantially unidirectional field provided they take about one half a period of the propagating wave to move from one element to an adjacent one assuming that the guide wavelength is long compared to the spacing between adjacent elements as is generally desirable. This is true whether electrons and the propagating waves are moving either in the same or opposite directions.

For backward wave type oscillations, the electron stream is made to interact with a particular backward or oppositely directed traveling wave. Such a wave of low amplitude is set up initially by noise components of the stream. For the amplification of this wave sufficient to sustain oscillations, the velocity of the electron stream is adjusted to be substantially equal to the phase velocity of a forward traveling spatial harmonic of this particular backward traveling wave. It can be shown that for oscillations, a relationship to be satisfied is that

$$v = \frac{\omega d}{\pi n - \theta} \quad (1)$$

where v is the average or D.-C. velocity of the electron stream past the interaction circuit, ω is the radian frequency of the wave to be amplified, d is the spacing between adjacent finger elements, θ is the phase shift between adjacent finger elements, and n is an integer. The velocity v of the electron stream is primarily determined by the accelerating voltage acting thereon, which is the potential difference between the cathode 13 and the structure 16. Lead-in conductors supplied from a suitable voltage source provide the necessary voltages on these elements. Additionally, both the spacing d and the phase shift θ can be adjusted as desired by varying the geometry of the wave guiding passage, and the dimensions and positioning of the finger elements.

Alternatively, if one pair of adjacent finger elements is considered as a single iterative section, the relationship to be met is that

$$v = \frac{\omega L}{2\pi n - \phi}$$

where L is the length of one iterative section (twice d) and ϕ is the phase shift along each section of the wave to be amplified (twice θ).

It is also necessary in order to initiate and sustain oscillations that the beam current be sufficient to exceed a certain starting current. To this end, it is merely necessary to increase the beam current until oscillations begin.

The intensity of this beam current is determined primarily by the voltages applied by lead-in conductors from a suitable voltage source to the cathode 13 and the beam forming and intensity control electrode 14. It is essential, of course, to feed back energy to sustain oscillations. This feedback is automatically supplied by the electron stream itself which is traveling in a direction opposite to the direction of the wave propagation and interacting therewith. For a more detailed description of the principles of backward wave oscillators, reference is made to my copending application, Serial No. 288,437, filed May 17, 1952.

It will be helpful at this point to describe briefly, by way of example, a method of construction found suitable for a hairpin circuit of the kind shown, designed for incorporation in a tube to have a center frequency of 50,000 megacycles (6 millimeters wavelength) for operation over a band 20,000 megacycles wide. The hairpins are made of gold-plated molybdenum wire of 2 mils diameter. This wire is wound by means of a precision helix-winding machine on a steel mandrel of substantially rectangular cross section, approximately 8 mils by 80 mils, having its sharp edges beveled smooth. The pitch of the winding along the mandrel is adjusted to be 10 mils for providing a center to center spacing of adjacent fingers of 5 mils, when two such windings are interleaved to form the interdigital circuits of Figs. 1 and 3. The mandrel, with the wire helix, is then inserted in a longitudinal groove in a copper piece which will form one of the two surfaces of the wave guiding passage from which a row of elements will extend. The depth of the groove is adjusted so that the height of that portion of the mandrel extending above the face of the copper piece, and consequently the height of the helix portion extending above that face corresponds to the desired finger length. The wire is then brazed to the edges of the groove which are gold plated to facilitate this end. A taper may be ground at either or both ends of the wound helix as desired in order to provide tapered sections at the ends of the interdigital circuit as shown in Figs. 1 and 3. The steel mandrel is then dissolved chemically, leaving the helix portions projecting from the copper piece to form a succession of U-shaped or hairpin-shaped finger elements. This process is repeated to obtain a second copper piece from which projects a similar row of "hairpins." The two copper pieces are properly aligned so that the two rows of "hairpins" are interleaved and then brazed together with two copper pieces which will form the two other sides of the wave guiding passage.

Fig. 3 shows a modification of the tube shown in Fig. 1 more particularly designed for amplifier applications. It is convenient to designate elements of this tube by reference numerals which exceed by 100 corresponding elements of the tube shown in Fig. 1. The principal difference is the provision of a wave guiding path from the collector or downstream end of the wave guiding passage 119 to an external coupling connection 137, similar to the wave guiding path provided at the electron source or upstream end of the passage 119 to the external coupling connection 136. This coupling connection 137 will furnish an input wave which is to be amplified when the tube is operated as a backward wave amplifier, or alternatively there will be supplied thereto an output wave which has been amplified when the tube is operated as a conventional forward wave amplifier. Accordingly, the main structure 116 will include a section 140 at the collector end which defines a wave guiding passage 141 forming a continuation of the wave guiding passage 119 to the tube envelope where a capacitive connection is made through the envelope to the external connection 137. As at the electron source end, the cross section of the wave guiding passage 119 gradually increases from the minimum portion along which extends the interdigital circuit to a size which matches that of the wave guiding passage 141, and for

facilitating connection to an external circuit, a right angle bend 142 is provided between wave guiding passages 119 and 141.

In this tube, it is also advantageous to decrease the loading gradually at the collector end of the wave guiding path 119 to make possible a broad band match. Accordingly, as at the electron source end, the length of the finger elements 131 is gradually decreased to effect a smooth transition to a condition of minimum loading.

It is important when this tube is operated as an amplifier to insure that the beam current does not exceed the value which will initiate backward type oscillations of the kind for which the tube of Fig. 1 is designed.

As has been indicated above, the tube shown in Fig. 3 can be adapted for operation either as a backward wave amplifier or as a more conventional forward wave amplifier. For operation in the backward wave mode, the velocity of the electron beam is adjusted to be equal to

$$\frac{\omega_c d}{n\pi - \theta}$$

where ω_c is the radian mid-band frequency of the operating range, d is the separation of adjacent elements, n is an integer, and θ is the phase shift between adjacent elements. Alternatively, for operation in a forward wave mode, the velocity of the electron stream is adjusted to be equal to

$$\frac{\omega_c d}{n\pi + \theta}$$

Summarizing, the present invention provides an improved form of interdigital filter-type wave circuit for use in various forms of traveling wave tubes, particularly those intended for operation at very short wavelengths, where the tube dimensions are also necessarily short. It is to be understood that the specific embodiments described above are illustrative of the general principles of the invention. Various other arrangements can be devised by one skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In electronic apparatus, a hollow wave guiding member, a linear array comprising two sets of U-shaped wire loops, the closed ends of said wire loops of each set extending inwardly from and the open ends thereof being attached to a different one of two opposite surfaces of said member, the closed ends of said two sets overlapping at the axis of the hollow wave guiding member and being interleaved in an interdigital pattern, and means for forming and projecting an electron stream through the region of overlapping of adjacent wire loops.

2. In electronic apparatus, a hollow wave guiding member, coupling means at one end of said member to be supplied with an input wave, coupling means at the other end of said member for removing an output wave, a linear array comprising two sets of spaced substantially U-shaped elements, the closed ends of the elements of each set extending inwardly from and the open ends thereof being attached to a different one of two opposite surfaces of said member, the closed ends of said two sets of elements overlapping at the axis of said wave guiding member and being interleaved in an interdigital pattern, and means for forming and projecting an electron stream through the region of overlapping of adjacent elements.

3. In an oscillator, an elongated hollow wave guiding member, means for forming an electron stream for longitudinal traversal of said member, a plurality of substantially U-shaped wire elements spaced apart in a linear array in the direction of electron flow, the closed ends of alternate elements extending from and the open ends thereof being attached to one surface of said member, the closed ends of adjacent elements extending from and the open ends being attached to opposite surfaces of said member in an interdigital pattern with the closed ends overlapping in the path of electron flow, means for ter-

minating the downstream end of said member to be substantially reflectionless, and a hollow wave guiding member coupled to the upstream end of the elongated hollow wave guiding member for abstracting oscillatory energy.

4. In an oscillator, an elongated hollow wave guiding member having an open end and an opposite end which is terminated to be substantially reflectionless, means for forming an electron stream for projection through said member from said open end towards said opposite end, a linear array of U-shaped wire loops spaced apart in the direction of electron flow, the closed ends of alternate wire loops of said array extending from and the open ends thereof being attached to the same side of said member, the closed ends of adjacent wire loops of said array extending from and the open ends thereof being attached to opposite sides of said wave guide member in an interdigital pattern with the closed ends of said wire loops overlapping in the path of electron flow; and means for connecting said elongated hollow wave guiding member to a second hollow wave guiding member at the open end of the elongated member for abstracting oscillatory energy for utilization, said last-mentioned means including a transition region wherein the elongated hollow member is gradually increased in its dimensions to merge into the second hollow member.

5. In an oscillator, an elongated hollow wave guiding member having one end closed and the opposite end open, dielectric means coated with lossy material adjacent the closed end for providing a reflectionless termination, means for projecting an electron stream through the hollow of said member from the open end towards the closed end, a plurality of substantially U-shaped wire elements spaced apart in a linear array in the direction of electron flow, the closed ends of alternate elements extending from and the open ends thereof being attached to the same side of the member, the closed ends of adjacent elements extending from and the open ends thereof being attached to opposite sides of the member in an interdigital pattern with the closed ends of said wire elements overlapping in the path of electron flow, and a second hollow wave guiding member coupled through said open end to the elongated member for abstracting oscillatory energy therefrom.

6. An oscillator according to claim 5 in which the electron stream has a velocity which is equal to

$$\frac{\omega d}{\pi n - \theta}$$

where ω is the oscillatory radian frequency of operation, d is the spacing between adjacent elements, n is an integer and θ is the radian phase shift between adjacent elements.

7. Electronic apparatus for amplifying electromagnetic waves having a midband radian frequency ω comprising an elongated hollow wave guiding member, means for forming and projecting an electron stream longitudinally through the hollow interior of said member, a hollow wave guide to be supplied with an input wave to be amplified coupled downstream along said member, a hollow wave guide for abstracting the amplified wave coupled upstream along said member, and a linear array of hairpin-shaped wire elements spaced along said member, the closed ends of alternate elements extending from and the open ends thereof being attached to one side of said member, the closed ends of adjacent elements extending from and the open ends thereof being attached to opposite sides of said member in an interdigital pattern with the closed ends of said elements overlapping in the path of electron flow, the velocity of the electron flow being equal to

$$\frac{\omega d}{\pi n - \theta}$$

where d is the spacing between adjacent elements, n is

an integer, and θ is the radian phase shift between adjacent elements.

8. In a device which utilizes the interaction between an electron stream and a traveling electromagnetic wave for amplifying the wave, means for projecting an electron stream along an extended path, means forming a conductive surface extending contiguous to the electron stream along a major portion of the length of said stream, a first plurality of substantially U-shaped wire loops extending from and attached to the conductive surface in a manner to have their closed ends encircle the stream, means forming a second conductive surface extending contiguous to the stream along a major portion of its length on the side of the stream opposite to the first conductive surface, and a second plurality of substantially U-shaped wire loops extending from and attached to the second conductive surface in a manner to have their closed ends encircle the stream, the U-shaped wire loops of said first and second plurality being interleaved in the direction of the electron stream to form an interdigital circuit.

9. In a device which utilizes the interaction between an electron stream and a traveling electromagnetic wave for amplifying the wave, means forming a hollow conductive wave guide, means for projecting an electron stream along the axis of said wave guide, a first plurality of substantially U-shaped wire loops each having its open end fixed to one side of the interior surface of said conductive wave guide and extending into the hollow wave guide to have its closed end encircle the electron stream, and a second plurality of substantially U-shaped wire elements each having its open end fixed to the opposite side of the interior surface of the conductive wave guide and extending into the hollow wave guide to have its closed end encircle the electron stream to form an interdigital circuit.

10. In a device which utilizes the interaction between an electron stream and a traveling electromagnetic wave for amplifying the wave, a transmission line for propagating an electromagnetic wave in a predetermined direction including a first conductive surface extending in a direction parallel to the direction of wave propagation, a second conductive surface extending in a direction substantially parallel to the first and spaced apart from each other in a direction transverse to the direction of wave propagation, and an array of U-shaped conductive finger elements along the interspace between said first and second conductive surfaces, said array comprising a first succession of elements, the open ends of which are attached to the first conductive surface and from which the closed ends extend more than half way but less than the entire way to the second surface and a second succession of elements, the open ends of which are attached to the second surface and from which the closed ends extend more than half way but less than the entire way to the first surface, the closed ends of said elements of the first succession being interleaved with those of the second in an interdigital pattern; and means for projecting a stream of electrons along an extended path in coupling proximity with a wave propagating along said circuit; said device being characterized in that the finger elements of the first and second successions are apertured and the aperture in each is aligned with the electron stream for passage therethrough of said stream.

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