Aug. 20, 1957

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2,803,777

RADIO FREQUENCY MATCHING DEVICES

Filed April 1, 1953

3 Sheets-Sheet 1

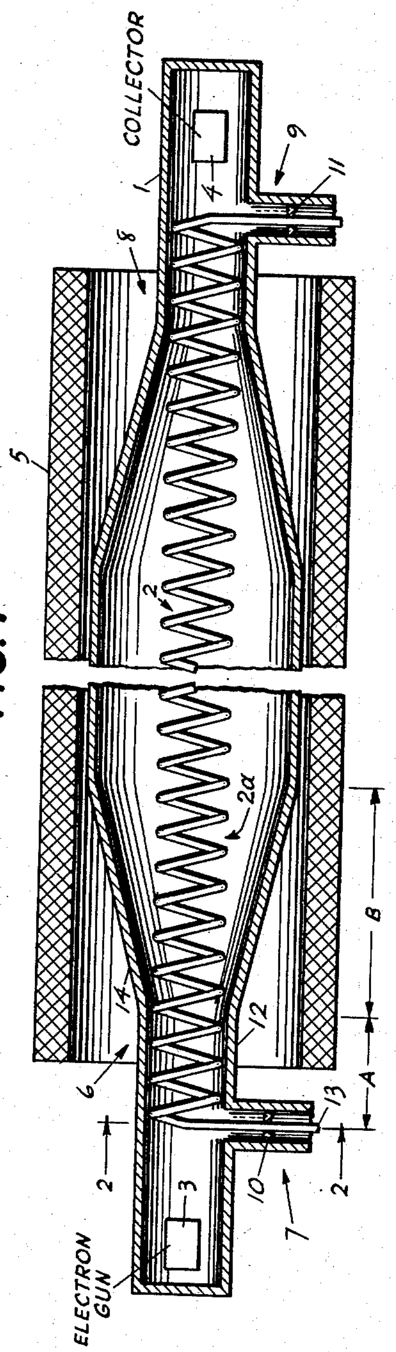

FIG. 1

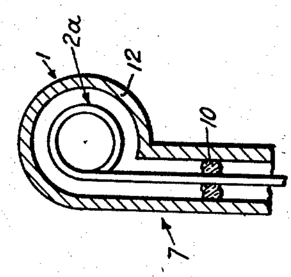

FIG. 2

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FIG. 3

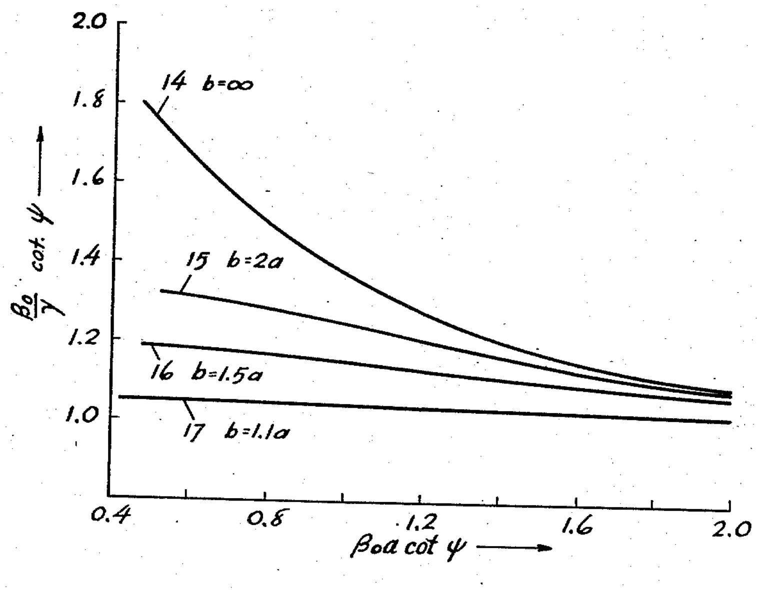

FIG. 4

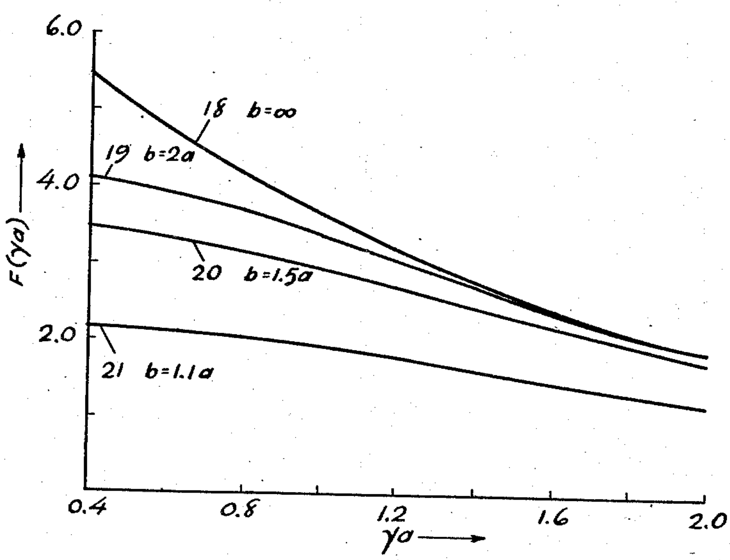

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FIG. 5

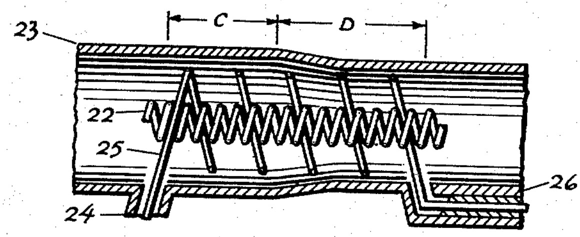


FIG. 6

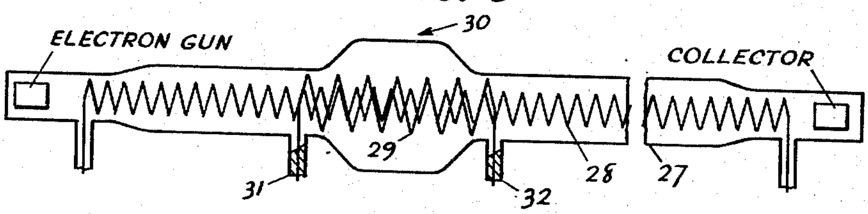


FIG. 6a

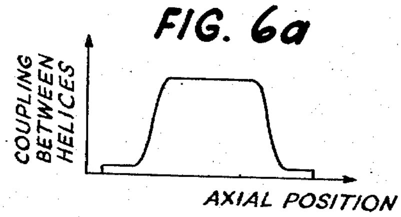
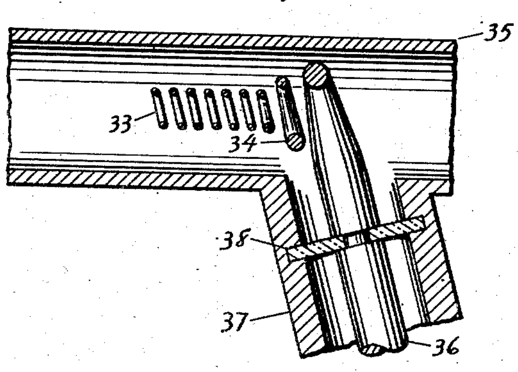


FIG. 7



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RADIO FREQUENCY MATCHING DEVICES

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17 Claims. (Cl. 315—3.5)

This invention relates to radio frequency matching devices and more particularly to means for obtaining a broadband match between radio frequency transmission lines and helical wave propagating structure of the type employed in traveling wave electron discharge devices and delay lines.

The traveling wave type of tube is particularly useful in broadband microwave systems since it is capable of amplifying radio frequency energy over an unusually broad band of frequencies. The tube includes a form of transmission line, usually a helix, for transmission of microwave energy for interaction with an electron beam closely associated with the line. The helical characteristic of the transmission line is such that the axial velocity of microwave signals conducted along the helical path is approximately the same as or slightly slower than the velocity of the electrons of the beam whereby the electrical field of the microwave signals interact with the electron beam for amplification of the microwave signals.

One of the major problems in the helix type of traveling wave tube is in obtaining a broadband impedance match between radio frequency transmission lines and the helical wave propagating structure. A helix type of traveling wave tube may have a useful operating frequency range of over two to one, with the useful range limited by the quality of the radio frequency match. It is known that to cover a two to one or greater frequency operating range, coaxial line radio frequency circuit connections are usually resorted to, since waveguide transmission lines have well known bandwidth limitations. The standard impedance of coaxial lines is normally of the order of 50 ohms, while the circuit impedance of traveling wave tube helices may be several hundred ohms. There is then, clearly, the problem of matching a low impedance coaxial radio frequency line to a helical radio frequency line of a much higher impedance than the coaxial line. Furthermore, it is well known that a conductor in close proximity to a conducting surface presents a surge impedance of the order of 50 ohms.

An object of this invention is the provision of means to provide a useful operating frequency range for a helix type of traveling wave tube of over two to one.

Another object of this invention is to provide means for matching a low impedance radio frequency line to a high impedance helical radio frequency line.

A feature of this invention is the provision of a transfer transmission line including a conducting cylinder in a given spaced relationship with the helical propagating structure wherein a portion thereof includes a tapered relationship between said propagating structure and said conducting cylinder, and a coupling helix disposed coaxially of said cylinder and tapered surface to provide an impedance match between a radio frequency transmission line, to which said helix is connected, and said propagating structure.

Another feature of this invention is the provision of a transfer transmission line including an outer conductor tapered to cooperate with the helical propagating structure in a manner to effectively reduce the impedance of said propagating structure to substantially 50 ohms and an extension of said outer conductor consistently spaced from said propagating structure to present a 50 ohm impedance for connection to a 50 ohm radio frequency transmission line.

Still another feature of this invention is the cooperation of an outer conductor with a tapered helical propagating structure arranged in a predetermined manner with respect to a radio frequency transmission line for achievement of the desired impedance match.

The above-mentioned and other features and objects of this invention will become more apparent by reference to the following description taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a longitudinal sectional view of a traveling wave electron discharge device illustrating an embodiment following the principles of this invention;

Fig. 2 is a cross-sectional view taken along line 2—2 of Fig. 1;

Fig. 3 is a graphical representation of the effect of the surrounding coaxial cylinder upon the velocity of propagation as a function of frequency;

Fig. 4 is a graphical representation of the effect of the coaxial conducting cylinder in the reduction of the helical impedance;

Fig. 5 is a longitudinal cross-sectional view of another embodiment for achieving radio frequency matching between a radio frequency transmission line and a helical wave structure without actual physical connection therebetween;

Figs. 6 and 6A diagrammatically illustrate still another embodiment of obtaining desired radio frequency matching following the principles of this invention; and

Fig. 7 is a longitudinal cross-sectional view illustrating another embodiment of this invention.

Referring to Fig. 1, there is illustrated a traveling wave electron discharge device comprising essentially an outer non-magnetic metallic conductive envelope or shell **1** surrounding a helical type wave propagating structure **2**. At one end of envelope **1** is located a suitable electron gun **3** for furnishing a concentrated stream of electrons which pass through the interior of helical conductor **2** for collection at a collector electrode **4** disposed in the opposite end of envelope **1**. The electron gun **3** and collector **4** may take any of the known configurations having electrical properties suitable for this application which are known in the art. The various electrode potentials and means for applying them have received extensive treatment in the prior art and as a result are omitted in the drawings of this application to simplify the figures thereof to more clearly illustrate the structural details for achieving the desired radio frequency matching in accordance with the principles of this invention. The traveling wave electron discharge device further is shown to have associated therewith a means **5** for producing a magnetic field whose lines of flux are parallel to the longitudinal axis of the tube for focusing and confining the electron beam parallel to the axis of the tube. Means **5** may be a solenoid so configured that the desired magnetic field is developed, or it may comprise a permanent magnet type electron-optical device for development of the desired axial magnetic field.

As hereinabove mentioned the characteristic impedance of helix **2** is of the order of several hundred ohms while radio frequency transmission lines of the wideband type, namely coaxial lines, may be of the order of 50 ohms. Therefore, it is necessary to provide an input matching section **6** capable of matching the 50 ohm transmission line **7** to helical propagation structure **2** and likewise an output matching section **8** to match the output transmission line **9** to propagating structure **2**. For such a matching arrangement to be effective, it should cooperate in the efficient transfer of energy for amplification from transmission line **7** to transmission line **9** without any appreciable loss of energy due to mismatch.

To assure a vacuum tight envelope **1**, it is desirous to provide in the input and output lines **7** and **9**, glass beads **10** and **11**, respectively.

Matching section **6**, substantially identical to matching section **8**, is shown to comprise a cylindrical coaxial portion **12** of envelope **1** in a predetermined spaced relationship with a circular conducting or helical wound wire to form a portion of the transfer transmission line having a characteristic impedance of the order of 50 ohms. It can be shown mathematically that the impedance of a transmission line consisting of a circular conducting wire, such as the wire employed in forming helix **2**, above an infinite plane conductor is given by

$$Z_0=\frac{1}{2}\pi\sqrt{\frac{\epsilon}{\mu}}\cosh^{-1}(h/b)$$

where h is the height of the wire center above the conducting plane, b is the radius of the wire, ϵ is the dielectric constant of the space between said wire and said conductor and μ is the permeability of that space. For practical purposes it has been found that this expression holds for surfaces of relative large radius of curvature. To properly meet the requirements established by the above equation the last turn of helix **2** should be brought out tangent to the helix diameter and joined to the center conductor **13** of the coaxial radio frequency line **7** as indicated in Fig. 2. The combination of conducting surface **12** and the proximity of the helical conductor **2** provides an impedance looking into transmission line **7** that can be made substantially equal to the characteristic impedance of transmission line **7** over an extremely wide frequency range. It has been ascertained that a radio frequency match with a maximum voltage standing wave ratio (V. S. W. R.) of 1.5 may be obtained for a frequency range of 300 to 1200 megacycles.

Thus, it is seen that the 50 ohm transmission line **7** can be matched to a 50 ohm transmission line comprising conducting portion **12** in close proximity to structure **2**. However, to achieve the advantages of the high impedance helical structure **2** for amplification of the radio frequency energy presented thereto from line **7**, it would be desirable to move the conducting cylinder **12** away from the active helix **2** known in this portion as the coupling helical conductor **2***a* as soon as possible after the input connection is made between helical conductor **2***a* and transmission line **7**. To accomplish this envelope **1** is flared out at tapered portion **14** to gradually increase the characteristic impedance of helix **2** in its relationship with conducting cylinder **1**. The length of the input connecting section **12** and tapered portion **14** may be in association with helix **2***a*, referred to as the transfer transmission line, shown to have a predetermined ratio for obtaining a broadband radio frequency match. It has been ascertained that with dimension A equal to 1 inch and dimension B equal to 2 inches that a match within 1.5 V. S. W. R. can be obtained from 450 megacycles to 1200 megacycles with a helix having a phase velocity corresponding to the velocity of 6500 volt electrons. Therefore, it is possible to match 50 ohm transmission line **7** to an active helical structure **2** employing only 3 inches of matching section similar to matching section **6** at frequencies ranging from 450 to 1200 megacycles. It will be found that the 3 inch section **6** provides a radio frequency match good for a lower frequency than required for a particular application, therefore, it is possible to reduce these dimensions to the extent that the desired match is obtained over only that portion of frequency bandwidth which is desirable. Such a reduction of the matching section or transfer transmission line provides a shorter tube for the particular application of interest and therefore will represent an economic saving.

The proximity of conducting cylinder or envelope **1** is seen from the above disclosure to have an appreciable effect upon the impedance of the helix **2** and as such may be employed as hereinabove outlined to obtain a desired radio frequency match between the transmission lines **7** and **9** and the helical structure **2**. It has further been discovered that conductor **1** tends to eliminate the dispersive character of the helical transmission line **2**. This dispersion characteristic is most pronounced at the low frequency end of the band and is extremely important when it is desired to operate the traveling wave tube over a frequency range of two to one or greater. Fig. 3 illustrates a plot of the effect of the surrounding coaxial cylinder **1** in flattening out the velocity of propagation on the helix **2** as a function of frequency.

The parameters of Fig. 3 are

$$\frac{\beta_0}{\gamma}\cot.\psi$$

a quantity nearly equal to the ratio of the axial velocity of a radio wave on a helix in a conducting cylinder to the velocity the wave would have if it were traveling at the speed of light along the direction of conduction, and $\beta_0 a \cot.\psi$, a quantity proportional to frequency, where ψ=the pitch angle of the helix,

$$\beta_0=2\pi\frac{f}{c},\ \beta=2\pi\frac{f}{v}$$

a=the helix mean radius, b=conducting cylinder radius, γ=the $\sqrt{\beta^2-\beta_0^2}$, c=the velocity of light propagation, f=the frequency of the radio wave propagated on the helix, and v=the velocity of propagation of the radio wave. Thus the curves **14**, **15**, **16**, and **17** indicate that the dispersive tendency of the helical structure **2** may be controlled by setting the inside diameter of the coaxial conducting cylinder with respect to the helical diameter.

Fig. 4 illustrates the effect of the outer coaxial conducting cylinder **1** upon reducing the helical impedance where the parameters are $F(\gamma a)$ which represents a factor in the impedance function

$$\frac{E_z^2}{\beta^2 P}=\left(\frac{\beta}{\beta_0}\right)\left(\frac{\gamma}{\beta}\right)^4 F^3(\gamma_a)$$

of a helix surrounded by a coaxial conducting cylinder where E_z is the peak electric field on the axis with power P flowing, and γa represents a quantity substantially proportional to frequency, where γ=the radial propagation constant, a=the radius of the helix and b=the radius of the conducting cylinder. Curves **18**, **19**, **20**, **21** indicate the effect of the outer conducting cylinder upon the helix impedance for the same conditions of helix and conducting cylinder radius as represented by the curves **14**, **15**, **16**, and **17** respectively of Fig. 3.

It will be obvious to one skilled in the art that a compromise must be reached between the helix impedance reduction and the reduction of dispersion by incorporating the radio frequency matching device in accordance with this invention such that the overall performance of a tube may be greatly improved by establishing the diameter of the coaxial cylinder at an appropriate value.

Not withstanding the importance of the dispersion of the radio wave by helical structure **2** the reduction of helical impedance plays an extremely important part in achieving a radio frequency match between a low impedance transmission line and the relatively large impedance helical line. The low impedance of the helical line means that more of the power in the radio propagating section of a traveling wave tube is flowing between the helical structure **2** and the conducting cylinder **1** than was flowing outside the helix when the conductor was absent or is removed from the proximity of the helix. Consequently, the presence of the outer conducting cylinder **1** has decreased the power flowing inside the helix. Therefore, it can be seen that the proximity of conducting cylinder 1 is a means whereby the amount of power flowing inside the helix with reference to the total power flowing may be controlled. For an example, for a helix in free space with a radial propagating constant equal to 1.5 and a total power P flowing, about ½ of P is flowing inside helical structure 2, while the remaining ½ of P is flowing outside the helical structure. On the other hand, with a conducting cylinder 1 having a diameter 1.1 times the helical diameter results in only about 1/25 of the power flowing inside the helix, while the remainder of P flows between the helical structure 2 and the cylinder 1. Therefore, it can be seen that by tapering the diameter of either the cylinder 1 or the helical structure 2, the power division between the helix or between coaxial helices may be controlled with respect to the distance along the axis.

Fig. 5 illustrates an embodiment where radio frequency power is to be transferred to a helix 22 under a radio frequency matched condition within a conducting cylinder or envelope 23 without actually making a physical connection with this helix 22. The power is fed by transmission line 24 to an outer helix 25, or coupling helical conductor. In region C the outer cylinder 23 is removed far enough from helix 25 such that the fields of the outer helix 25 are strong on its axis and hence will interact with the fields of the inner helix 22 in such a manner that the power carried by helix 25 will be transferred to helix 22. In region D the outer cylinder is gradually tapered closer to the outer helix 25 such that the outer helix essentially has no interaction with the inner helix 22 since the power remaining on the helix 25 will be located between the outer conductor 23 and this helix 25. Helix 25 after encountering region D may be terminated at 26 in a matched load thereby providing structure incorporating the characteristics of a helix in association with a conducting cylinder to provide a smooth transition of power between an outer helix or coupling helical conductor, and an inner coaxial helix for amplification of this power as is the normal behavior of a traveling wave type device.

The principles hereinabove outlined in connection with Figs. 1, 2, and 5 illustrate the possibility of employing a conducting cylinder configured to cooperate with coaxial helices for the extraction of power flowing on the inner one of said coaxial helices. Fig. 6 illustrates such an application wherein the outer conducting cylinder 27 is concentric to an inner helix 28 and an outer coaxial helix 29, or coupling helical conductor, employed to remove radio frequency power flowing in either direction on inner helix 28. To provide a reflectionless transmission, it is desired to provide a tapering of the coupling between the helices 28 and 29 along the axis of the conducting cylinder 27. This is accomplished by a proper tapering of the diameter of the outer cylinder 27 as indicated at portion 30 of the outer conductor 27 so that at the ends at the outer helix very little interaction occurs between the coaxial helices. However, the interaction at the center is relatively strong and the power from the main or inner helix 28 may be substantially removed therefrom as indicated in the curve of Fig. 6A. The power removed may then be coupled through either of the terminals 31 and 32 depending upon the direction of power flow and the appropriate load into which it is desired to couple this power. The employment of this embodiment will allow attenuation of reflected waves without employing lossy material in contact with the propagating structure wherein coupling helix 29 is disposed in the forward portion of a traveling wave tube in a manner to produce the desired amplification therein.

In all of the embodiments of this invention a problem associated with such high power tubes is the power handling capabilities of the vacuum seals such as seals 10 and 11 of Fig. 1 in the radio frequency transmission lines. Consequently, in high power tubes it may be desirable to transform from a small diameter helical wire to a larger size coaxial line prior to encountering such a vacuum seal.

An embodiment of Fig. 7 illustrates a suitable arrangement for transforming from a small diameter helical wound wire to a large size coaxial line in or near the output section of the helix.

Referring to Fig. 7, there is illustrated that the helical conductor 33 in the last few turns thereof is tapered to a larger size as indicated at 34. At the same time the main diameter of the helical wound wire is tapered in a manner such that the helical conductor is moved into closer proximity with the outer conductor 35 until the impedance of the transfer transmission line including the helical conductor 33 adjacent to the outer conductor in region 34 has a characteristic impedance of the order of 50 ohms. As the diameter of the helix is being increased the diameter of the conductor forming the helix may be increased until the diameter substantially approximates the diameter of the inner conductor 36 of the radio frequency line 37. This larger diameter wire enables the employment of larger vacuum seals 38 in the radio frequency line which provides more realistic power handling capability for vacuum seals.

While I have described above the principles of this invention in connection with specific apparatus, it is to be clearly understood that this description is made only by way of example and not as a limitation to the scope of my invention as set forth in the objects thereof and in the accompanying claims.

I claim:

1. A broadband radio frequency matching device for use between a low impedance transmission line of the coaxial type and a high impedance wave propagating structure of the helical type, comprising a transfer transmission line including a conducting cylinder and a coupling helical conductor disposed within and coaxially of said cylinder, said transfer line being characterized by three sections, the first section thereof having a structural relationship in which a constant narrow spacing is provided between said cylinder and said coupling helical conductor for a longitudinal length equal approximately to one third the length of said transfer line to extend the frequency range over which an impedance match is accomplished, the second section thereof having a structural relationship in which a relatively wide spacing is provided between said cylinder and said coupling helical conductor for a predetermined longitudinal length of said transfer line, and the third section thereof having a structural relationship in which the spacing between said cylinder and said coupling helical conductor is varied gradually between the wide and narrow spacing of the first and second sections.

2. A device according to claim 1, wherein the cylindrical portion of said third section is tapered to provide said variation in spacing between said cylinder and said coupling helical conductor.

3. A device according to claim 1, wherein the turns of said coupling helical conductor of said third section is varied in diameter to provide said variation in spacing between said cylinder and said coupling helical conductor.

4. A device according to claim 3, wherein the diameter of the wire forming said coupling helical conductor is gradually increased to provide direct coupling to large diameter coaxial transmission lines.

5. A device according to claim 1, wherein said propagating structure includes a helical transmission line and the coupling helical conductor of said third section is connected to said helical transmission line as a continuation thereof.

6. A device according to claim 5, wherein the turns of said coupling helical conductor of said third section is varied in diameter to provide said variation in spacing between asid cylinder and said coupling helical conductor.

7. A device according to claim 1, wherein said propagating structure includes a helical transmission line and said coupling helical conductor is disposed in concentric relation to said helical transmission line.

8. A device according to claim 7, wherein the conducting cylinder of said third section is tapered to provide said variation in spacing between said cylinder and said coupling helical conductor.

9. A device according to claim 7, wherein said coupling helical conductor is appropriately terminated at the end thereof for a predetermined matched coupling of energy between said propagating structure and said coupling helical conductor.

10. A device according to claim 1, wherein said propagating structure includes a helical transmission line and said coupling helical conductor is disposed in concentric relation to said helical transmission line and a second substantially identical transfer transmission line is disposed coaxially of said helical transmission line in a manner whereby the gradual variation of the third section of said transfer line is diametrically opposed to the gradual variation of the third section of the original transfer line.

11. A broadband radio frequency matching device for use between a low impedance transmission line of the coaxial type and a high impedance wave propagating structure of the helical type, comprising a transfer transmission line including a conducting cylinder and a coupling helical conductor disposed within and coaxially of said cylinder, said transfer line being characterized by three sections, the first section thereof having a structural relationship in which a constant narrow spacing is provided between said cylinder and said coupling helical conductor for a longitudinal length equal approximately to one third the length of said transfer line to extend the frequency range over which an impedance match is accomplished and to present an impedance equal substantially to the impedance of said coaxial line, the second section thereof having a structural relationship in which a relatively wide spacing is provided between said cylinder and said coupling helical conductor for a predetermined longitudinal length of said transfer line to present an impedance equal substantially to the impedance of said high impedance wave propagating structure, and the third section thereof having a structural relationship in which the spacing between said cylinder and said coupling helical conductor is varied gradually between the wide and narrow spacing of the first and second sections to effect substantially reflectionless transfer of energy therebetween.

12. A broadband radio frequency matching device for use between a low impedance transmission line of the coaxial type and a high impedance wave propagating structure of the helical type, comprising first and second transfer transmission lines, each of said transfer transmission lines including a conducting cylinder and a coupling helical conductor disposed within and coaxially of said cylinder, each of said transfer lines being characterized by three sections, the first section thereof having a structural relationship in which a constant narrow spacing is provided between said cylinder and said coupling helical conductor for a predetermined substantial longitudinal length of said transfer line to extend the frequency range over which an impedance match is accomplished, the second section thereof having a structural relationship in which a wide spacing is provided between said cylinder and said coupling helical conductor for a predetermined longitudinal length of each of said transfer lines, and the third section thereof having a structural relationship in which the spacing between said cylinder and said coupling helical conductor is varied gradually between the wide and narrow spacing of the first and second sections, said propagating structure including a helical transmission line and said coupling helical conductor of said second transfer line being a continuation of said coupling helical conductor of said first transfer line and being disposed in concentric relation to said helical transmission line, said first and said second transfer lines being disposed in a manner whereby said second sections thereof are continuous and the gradual variations of said third sections are oppositely disposed, whereby a tight coupling is established between said continuous coupling helical conductor and said helical transmission line.

13. A device according to claim 12, wherein said coupling helical conductor is appropriately terminated at the ends thereof for predetermined matched coupling of energy between said coupling helical conductor and said propagating structure.

14. In a traveling wave electron discharge device including a vacuum housing, a collector electrode at one end of said housing, means for producing an electron beam for flow along a given path between said beam producing means and said collector electrode at the other end of said housing and a radio frequency propagating structure disposed adjacent said path within said housing to enable reaction between the electrons of said beam and radio frequency energy propagated along said structure; a coupling section disposed along said path within said housing intermediate said beam producing means and said collector electrode and in coaxial coupling relation to said propagating structure to couple reflected wave energy in a reflectionless manner from said propagating structure.

15. In a device according to claim 14, wherein said coupling section includes a helical coupling conductor concentric to said propagating structure for a predetermined length thereof and a termination at one end of said helical coupling conductor to attenuate the reflected wave energy coupled from said propagating structure.

16. In a device according to claim 15, wherein said coupling section includes a conducting cylinder having a predetermined spaced relationship with respect to said helical coupling conductor whereby a tight coupling is established between said coupling conductor and said propagating structure.

17. In a device according to claim 14, wherein said coupling section includes a helical coupling conductor and a conducting cylinder concentric to said propagating structure whereby a predetermined spaced relationship between said coupling conductor and said cylinder provides a tight coupling between said coupling conductor and said propagating structure.

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