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2,905,858

IMPEDANCE MATCHING BY MEANS OF COUPLED HELICES

Filed June 30, 1953

2 Sheets-Sheet 1

FIG. 1

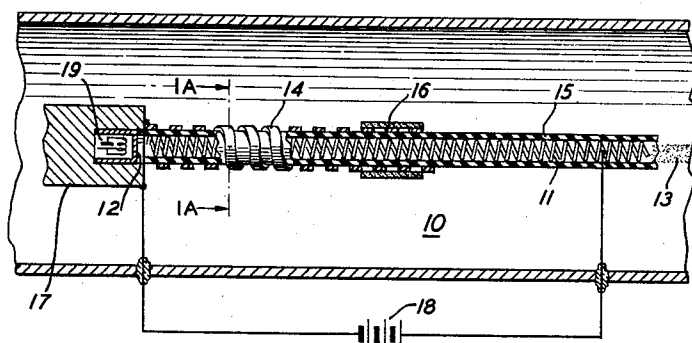


FIG. 1A

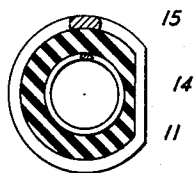
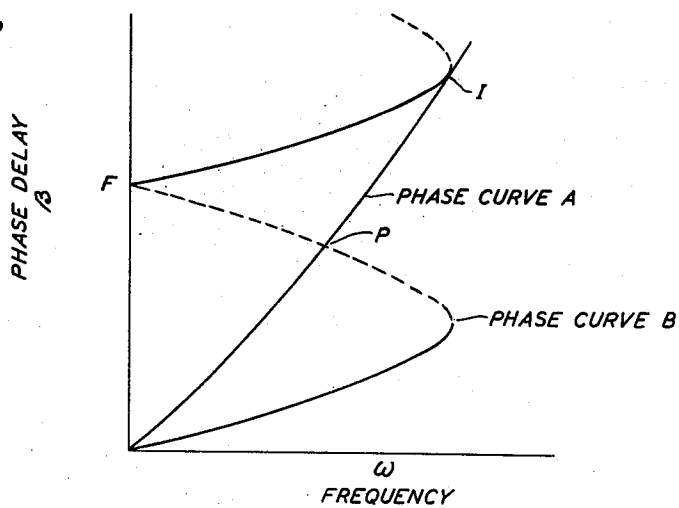


FIG. 2



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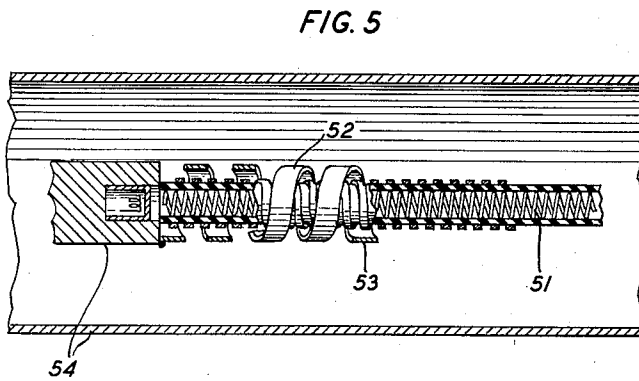
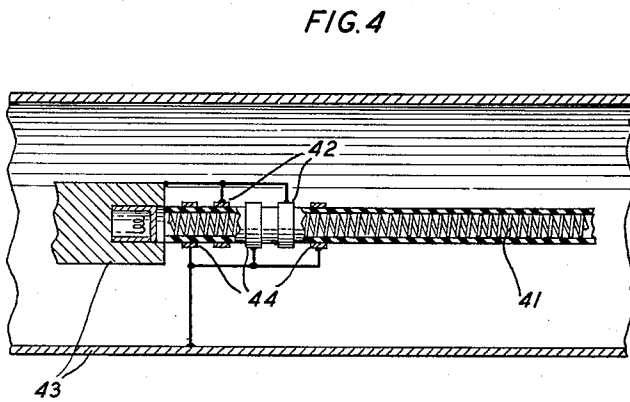
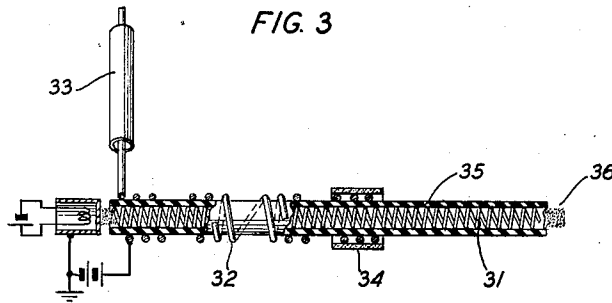
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2 Sheets-Sheet 2



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IMPEDANCE MATCHING BY MEANS OF COUPLED HELICES

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16 Claims. (Cl. 315—39.3)

This invention relates to impedance matching and more particularly it relates to impedance matching between circuits having greatly differing impedances.

An object of this invention is to provide an improved impedance matching arrangement for use in traveling wave tubes.

One common form of traveling wave tube employs an electron stream in combination with a concentric wave propagating helix which is adapted to propagate an electro-magnetic wave at substantially the same velocity as that of the electron stream. When a signal wave travels along this helix in synchronism with the stream it is able to extract kinetic energy from the electrons and thereby to increase its own energy. It has been found, however, that under certain conditions this kind of amplification is unstable because of the presence of waves backward traveling with respect to the electron stream which are of sufficient amplitude to sustain oscillations. Since such oscillations lower tube efficiency and produce other unwanted results, it is desirable therefore to prevent them by, for example, reducing below a critical value the feedback energy supplied by the backward traveling waves. To this end it is very helpful to eliminate so far as possible any impedance mismatches between input or output circuits and the helix circuit in the tube since these mismatches would otherwise cause wave reflections. Moreover, frequently this matching is made more difficult than it otherwise would be by the large difference between the impedance of conveniently available input or output circuits and the impedance of the tube helix.

Previous to this invention, one way of matching these impedances has been to place a shorting bar or its equivalent across several turns of the tube helix near the end thereof thereby forming a T or π type filter between the helix and an input or output line. Such a filter has impedance transforming properties but unfortunately the frequency band width over which such action is efficient is very narrow. A second method similar in purpose but producing a somewhat broader band width consists of tapering either or both the diameter and pitch of the tube helix near its ends. Where the impedance difference between the tube helix and the external wave circuits is small this serves to reduce wave reflections to a satisfactory level but when this difference is large, these reflections become objectionable. To eliminate such drawbacks the present invention is designed to provide an arrangement whereby a substantially reflectionless match over an acceptable band width can be obtained between circuits having greatly differing impedances.

In accordance with the present invention and in one embodiment thereof a ribbon helix of low impedance is asymmetrically placed in coupling relation around the wave propagating helix in a traveling wave tube. The pitch of the outer helix is made substantially greater than the pitch of the inner helix and by this means its impedance is made appreciably smaller than that of the inner helix.

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Impedance matching between the two helices is accomplished simply by adjusting the pitch of the outer helix so that a component of a wave present on it travels therealong at the same axial phase velocity as that of a wave on the inner helix. This synchronization of phase velocity takes place by spatial harmonic interaction whereby the wave on the outer helix traveling at greater axial phase velocity than that of a wave on the inner helix interacts with the latter wave only at given intervals so that it appears to be moving in synchronism with it.

A more complete understanding of this invention, together with a better appreciation of its advantages will best be gained from a study of the following description given in connection with the accompanying drawings, in which:

Fig. 1 is a schematic representation of the input portion of a helical traveling wave tube in which the tube amplifying helix is coupled at an end thereof to an outer ribbon helix;

Fig. 1A is a cross section of the helices in Fig. 1 taken as indicated by line 1A—1A;

Fig. 2 is a plot of the phase constant versus frequency characteristics for two helices such as shown in Fig. 1;

Fig. 3 shows an arrangement similar to that in Fig. 1 in which the outer helix is wire wound with non-uniform pitch;

Fig. 4 shows an arrangement similar in operation to that in Fig. 1 in which a filter type spatial harmonic circuit is coupled to the inner tube amplifying helix; and

Fig. 5 shows a modification of the embodiment of Fig. 1 in which coupling to the inner helix takes place by means of an intermediate helix inserted between it and the outer helix.

Referring now more particularly to the drawings, Fig. 1 shows by way of illustration a side section of part of a helical traveling wave tube 10 in which helix 11 is the principal wave propagating circuit. Electron gun 12, positioned to the left of this helix, is aligned with respect thereto so that electron stream 13 flows axially within helix 11. Ribbon helix 14 surrounding the left end portion of this helix is separated therefrom by insulating material 15 which is preferably a low-loss dielectric material such as quartz. The right end of helix 14 is terminated in a nonreflecting impedance 16 which may be placed around the last several turns as shown. The other end of helix 14 is connected to and forms a continuation of the inner conductor of coaxial input line 17. The outer conductor of this line forms an over-all envelope for the tube and extends on beyond the output end of the tube, which, although not shown, may be similar to the input end. Power supply 18 for accelerating electron stream 13 and cathode heater battery 19 may be connected as shown in Fig. 1. Other auxiliary circuits not shown here can be substantially the same as those customarily provided for conventional traveling wave tubes and their use is to be understood.

It will be noted from the drawing that the pitch of helix 14 is opposite with respect to and much larger than the pitch of helix 11. Because of this, its impedance is much lower than that of the helix it surrounds and its length is appreciably shorter than would be necessary if it were wound in the same sense as the inner helix. The lengths of helix 14 and of the other spatial harmonic circuits illustrated herein depend upon the tightness of coupling and on the order of the mode of operation. In general these lengths should be sufficient to insure substantially complete energy transfer.

In the absence of asymmetry in the physical relation of inner to outer helices the useful field components of the wave on the outer helix would be self-canceling in their effect on the inner helix. This requirement of asymmetry

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is easily met, however, by providing, for example, a flat side on helix 14 as is shown in the enlarged cross section thereof shown in Fig. 1A taken as indicated by line 1A—1A in Fig. 1. The inner flat surface of the outer helix is wound in close proximity to the outer surface of helix 11 so that the field coupling between the two circuits will be large. The coupling between the two circuits is best described as being periodically variable along the coextensive lengths of the two circuits. Thus the flat side on helix 14 is a region of strong coupling which occurs periodically along the length of helix 14.

The operation of the embodiment in Fig. 1 will perhaps best be understood from a consideration of Fig. 2. This figure shows by way of example the phase delay β versus frequency ω characteristics for two helices such as those shown in Fig. 1. Curve A, which may be taken to represent the characteristic of helix 11, is approximately a straight line through the origin for the portion of the characteristic shown. This linearity results from the essentially constant phase velocity of propagation, which for any circuit is given by

$$\frac{\omega}{\beta}$$

of a wave traveling along a helix whose dimensions are small relative to a wavelength. Curve B, representing the characteristic of helix 14, shows by the solid portion of the curve for values of β below the value F that the axial phase velocity of the fundamental component of a wave traveling along this helix is roughly constant with frequency and is much higher than the velocity of a wave along helix 11 over this range of frequency. No synchronization is possible therefore between this fundamental component and a wave on helix 11. It is evident, however, from an inspection of Fig. 2 that at certain frequencies, fixed by the intersections of curves A and B, the velocities of wave components on the two helices are the same. The first of these intersections, point P, represents zero velocity difference between the first backward traveling spatial harmonic components on helix 14 and the main wave on helix 11. This kind of synchronization is useful when the signal wave on helix 11 is backward traveling with respect to the direction of electron flow. For the structure illustrated in Fig. 1, however, where the signal is forward traveling synchronization with forward traveling components on helix 14 is necessary. The first of such points of synchronization occurs at intersection I in Fig. 2 where the first forward spatial harmonic on helix 14 will travel with substantially the same velocity as that of the signal wave on the inner helix. When curve A is tangent to curve B as shown there is an appreciable band width of frequency over which the two velocities are equal. Although higher order modes of synchronization, both backward and forward, are possible, in general it is desirable to utilize a low order component of the fundamental wave because as the order increases the amplitude decreases. Accordingly the pitch of helix 14 is preferably chosen so that the first spatial harmonic wave on it will synchronize with the wave on the inner helix.

The magnitude of the slope of the phase delay versus frequency characteristic of a circuit is proportional to its impedance and so it can be seen in Fig. 2 from curves A and B in the vicinity of intersection I that the impedance of helix 14 is much lower than that of helix 11. Therefore, by properly adjusting the pitch and the phase delay characteristic of the outer helix it is readily apparent that a low impedance line can be matched to a high impedance circuit.

In obtaining a thorough understanding of the invention it is helpful to consider from a mathematical standpoint the relationship between the fundamental component of the wave on helix 14 and its spatial harmonic components. Let φ be the phase displacement in radians between adjacent turns and let d be the center to center

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distance between turns. Then the axial component E_z of the electric field of the wave traveling therealong is given by the following expression:

$$E_z = F(z) e^{j\omega t} \quad (1)$$

5 where

$$F(z) = \sum_{n=-\infty}^{n=\infty} A_n e^{-(j2\pi n + \varphi) \frac{z}{d}}$$

10 Thus E_z is represented as an infinite sum of traveling waves each with a different phase velocity v given by

$$v = \frac{\omega d}{2\pi n + \varphi} \quad (2)$$

15 where n is an integer between $+\infty$ and $-\infty$. By adjusting the pitch and diameter of helix 14 so that the ratio

$$\frac{2\pi n + \varphi}{d}$$

20 is equal to the axial phase delay constant β of the inner helix for a given value of n , substantially complete transfer of energy between the two helices can be obtained.

Fig. 3 shows a second illustrative embodiment of the invention in which a traveling wave tube helix 31 is surrounded by round wire helix 32 having a nonuniform pitch. This outer helix, because of its variable pitch, functions in substantially the same way as does helix 14 in Fig. 1. Here, however, instead of forming a continuation of a coaxial line surrounding other tube elements, its left-hand end may be connected to a line 33 as shown. A matched impedance 34 is connected to the other end of helix 32 in order to eliminate reflections of wave energy at this point. The left-hand end of helix 31 may also be so terminated although this is not shown in the drawing. Glass insulation 35 serves both as a means of separating the two helices and as an air-tight envelope surrounding electron stream 36.

Fig. 4 shows a third possible embodiment of the invention in which a filter type spatial harmonic circuit is placed surrounding a traveling wave tube helix 41. This filter circuit consists of a succession of rings alternately connected in two groups, one of which (group 42) forms a continuation of the inner conductor of input coaxial cable 43. By grounding the other group (group 44) a periodic shielding of the electric field in this region is produced, thereby causing the generation of spatial harmonic components of the principal wave traveling along this section. The coaction of this circuit with the helix it surrounds, as well as their remaining structural details are substantially the same as those of the circuit of Fig. 1.

Fig. 5 shows an illustrative embodiment of the invention in which impedance matching between an inner wave helix 51 of a traveling wave tube and an outer ribbon helix 52 takes place in two steps instead of one as previously. This is accomplished by inserting an intermediate ribbon helix 53 between the inner and outer circuits. To secure economy of space while at the same time insuring strong coupling, the intermediate helix should be wound in a sense opposite to that of the other two helices and both it and the outer helix should be asymmetrically placed around the inner helix. Other structural details, of this arrangement, can be similar to those described previously in connection with Fig. 1.

55 Since the impedances of coaxial line 54 and helix 52 are matched, the standing wave ratio at their junction is substantially unity and all the energy from the line flows into this helix. By adjusting the pitch of intermediate helix 53 so that the velocity of a low order spatial harmonic component of a wave on it is substantially the same as the velocity of a higher order component of the wave on the outer helix, energy transfer between the two helices takes place. Energy transfer between helices 53 and 51 takes place in a way which has previously been set forth. Thus by proper adjustment of all these fac- 75

tors, a double step-up of impedance from line 54 to helix 51 is obtained.

It is apparent from the embodiment of Fig. 5 that a helix such as helix 53 may be used instead of round wire inner helix 11 in Fig. 1. Other obvious substitutes for helix 11 include a filter type circuit such as shown in Fig. 4 and a bifilar helix. In general, for the purposes of this invention, any appropriate spatial harmonic circuit may be coupled to any other suitable circuit, spatial harmonic or otherwise, in a way similar to those set forth herein. Other changes or modifications of the embodiments illustrated will occur to those skilled in the art and may be made without departing from the spirit or scope of this invention.

What is claimed is:

1. In combination, a first wave propagating circuit having a given impedance and adapted to propagate a first electromagnetic wave along an axis with a given phase velocity, a second wave propagating circuit having an impedance different from said given impedance and adapted to propagate a second electromagnetic wave in a direction parallel to said axis with a phase velocity different from said given phase velocity, means for applying a wave signal to one of said circuits, said second circuit being insulated from said first circuit and positioned in electromagnetic field coupling relation to said first circuit only at periodic intervals determined so that said second wave appears to be traveling in the same direction as said first wave with substantially the same phase velocity, whereby wave energy is coupled between said first and second circuits at said intervals.

2. The combination of elements as in claim 1 in which said first and second circuits are helices of first and second pitches respectively.

3. The combination of elements as in claim 1 in which said second circuit surrounds said first circuit and is shielded therefrom at periodic intervals spaced along the axis of wave propagation.

4. A traveling wave tube including, a coaxial transmission line having an outer conductor and an inner conductor a length of said inner conductor being removed along a section of said line, a first wave propagating circuit adapted to propagate a spatial harmonic component of a wave on said transmission line at a phase velocity v and forming a continuation of said inner conductor along part of said section, a second wave propagating circuit disposed along said section and adapted to propagate a wave component of a wave at substantially the velocity v , said first circuit having a plurality of spaced portions along the length thereof having a wave energy coupling characteristic with said second circuit greater than the wave energy coupling characteristic of the remaining portions of said first circuit with said second circuit whereby wave energy is coupled between said first and second circuits at said portions, and means for forming and projecting an electron stream in field coupling relation to said second circuit.

5. The combination of elements as in claim 4 in which said first circuit is a ribbon helix.

6. The combination of elements as in claim 4 in which said second circuit is a wire helix having a common axis with said inner conductor, and said electron stream is projected along said axis.

7. In combination, a wave transmission helix having a phase delay characteristic of β radians per unit length, and a wave propagating circuit surrounding a portion of the length of said transmission helix for transferring wave energy between said helix and said circuit, said circuit having a plurality of spaced portions along the length thereof having a wave energy coupling characteristic with said helix greater than the wave energy coupling characteristic of the remaining portions of said circuit with said helix, said circuit having a phase delay between turns of φ radians, a spacing between turns d and a diameter such that

$$\frac{2\pi n + \varphi}{d}$$

is substantially equal to β , where n is any integer other than zero whereby wave energy is coupled between said helix and said circuit at said portions.

8. In combination, first means for propagating a spatial harmonic component of a wave along a given direction with a phase velocity v , said component having a frequency ω , and second means in proximity to said first means and coextensive therewith for a portion of its length and adapted to propagate a component of a wave having a frequency ω along said given direction with a velocity v , said first means having a plurality of spaced portions along the length thereof coextensive with said second means having a field coupling characteristic with said second means greater than the field coupling characteristic of the remaining portions of said first means with said second means whereby wave energy is coupled between said second means and said first means at said spaced portions.

9. In combination, impedance matching means including a plurality of coextensive wave propagating circuits each having a different impedance and each placed adjacent to and insulated from another of said circuits for transferring wave energy between adjacent circuits, a first one of said circuits adapted so that at a given frequency the phase delay in radians per unit length of a spatial harmonic component of a wave traveling therealong in a given direction is substantially equal to the phase delay in radians per unit length of a wave traveling along an adjacent circuit in a parallel direction, said first one of said circuits having a plurality of spaced portions along the length thereof coextensive with said adjacent circuit having a wave energy coupling characteristic with said adjacent circuit greater than the wave energy coupling characteristic of the remaining portions of said first one of said circuits with said adjacent circuit whereby wave energy is coupled between said first one of said circuits and said adjacent circuit.

10. In combination, a source of a high frequency signal wave, a transmission line of given impedance connected to said source, a first wave transmission circuit of matched impedance connected to said line and adapted to propagate along a given direction with a phase velocity v a spatial harmonic component of the wave thereon, and a second wave transmission circuit of different impedance placed in proximity to said first circuit and coextensive therewith over a portion of its length and adapted to propagate parallel to said given direction with substantially the velocity v a component of a wave having the same frequency as said signal wave, said first circuit having a plurality of spaced portions along the length thereof coextensive with said second circuit having a wave energy coupling characteristic with said second circuit greater than the wave energy coupling characteristic of the remaining portions of said first circuit with said second circuit whereby wave energy is coupled between said first and second circuits at said spaced portions.

11. The combination of elements as in claim 9 in which the first one of said circuits is a ribbon wire helix having a pitch d and adapted to give spatial harmonic wave propagation, and a second one of said circuits is a round wire helix having a pitch less than b and being asymmetrically surrounded by said ribbon helix.

12. The combination of elements as in claim 9 in which the first one of said circuits is a helix of low impedance adapted to support spatial harmonic wave propagation, a second one of said circuits is a helix of intermediate impedance adapted to support spatial harmonic wave propagation, and a third one of said circuits is a helix of high impedance whose dimensions are small enough so that it will not support spatial harmonic wave propagation.

13. The combination of elements as in claim 9 in which the first one of said circuits is a wire wound helix of non-uniform pitch, and a second one of said circuits is a wire wound helix of uniform pitch.

14. The combination of elements as in claim 9 in which a first one of said circuits is an iterative filter type circuit adapted to support spatial harmonic wave propagation, and a second one of said circuits is a wire wound helix of uniform pitch.

15. The combination of elements as in claim 10 in which said first circuit is adapted to propagate with velocity v the first forward traveling spatial harmonic component of the wave traveling therealong and said second circuit is adapted to propagate with velocity v a wave not having spatial harmonic components.

16. The combination of elements as in claim 10 in which said second circuit is adapted to propagate with velocity v the first forward traveling spatial harmonic component of the wave traveling therealong and said first circuit is adapted to propagate a spatial harmonic wave.

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