Oct. 11, 1960 B. J. DUNCAN 2,956,246

MICROWAVE UNILATERAL TRANSDUCER

Filed July 8, 1957 3 Sheets-Sheet 1

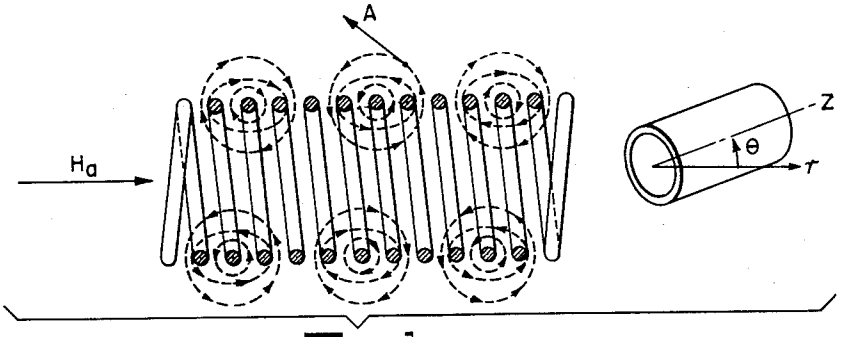


FIG. 1

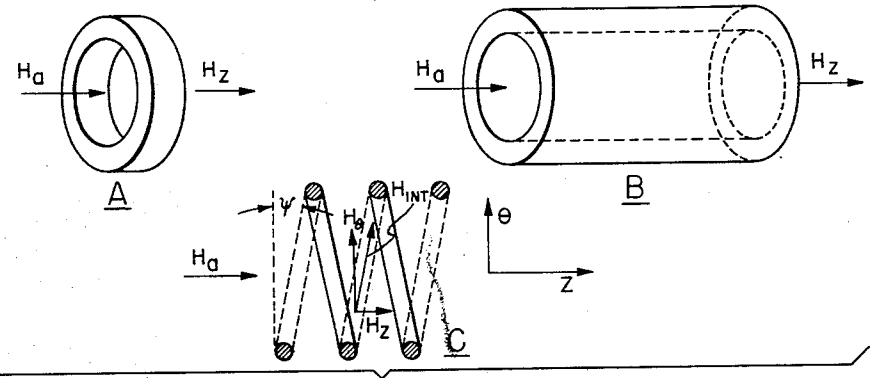


FIG. 2

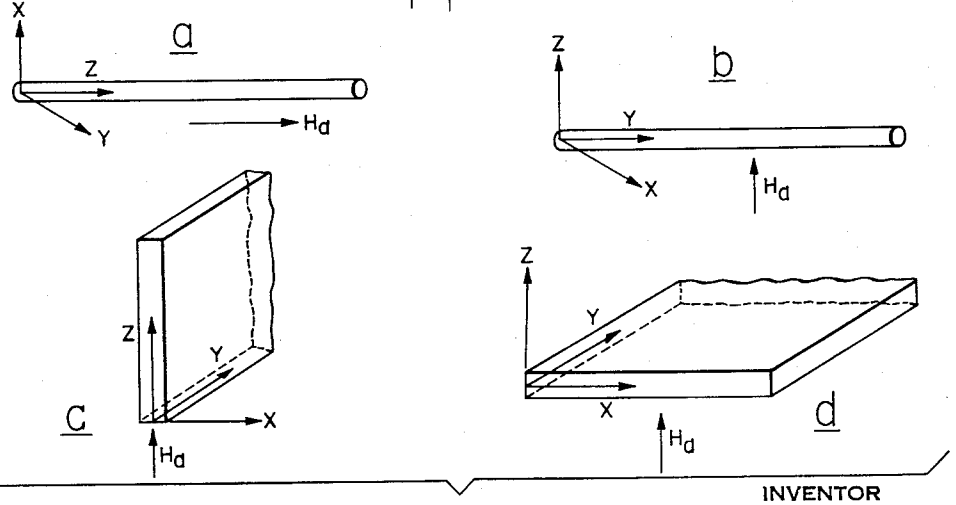


FIG. 3

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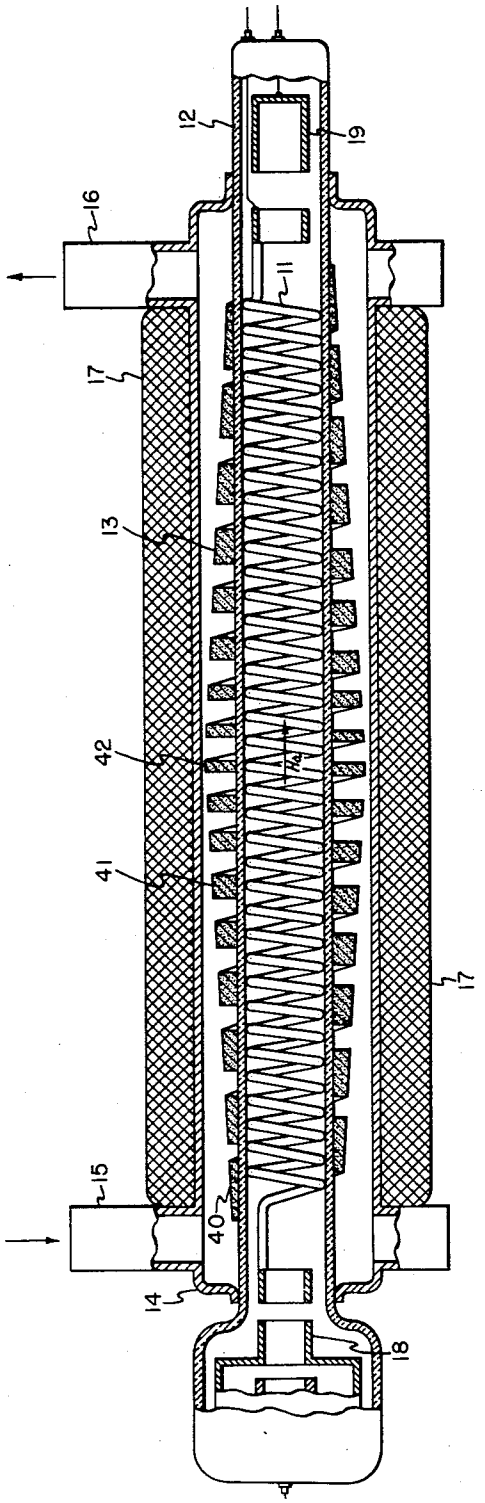


FIG. 4

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MICROWAVE UNILATERAL TRANSDUCER

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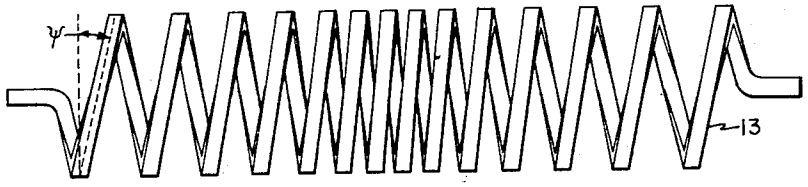


FIG. 5

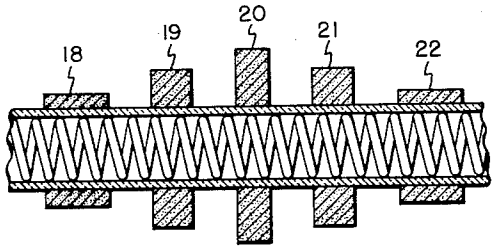


FIG. 6

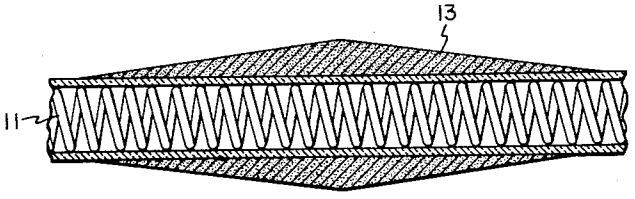


FIG. 7

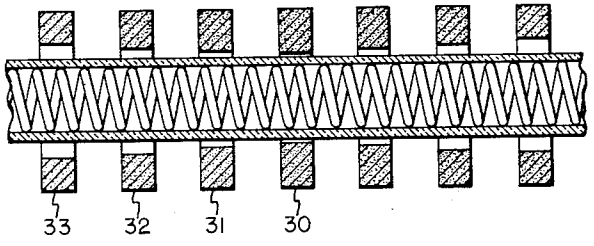


FIG. 8

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2,956,246

MICROWAVE UNILATERAL TRANSDUCER

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Filed July 8, 1957, Ser. No. 670,586

3 Claims. (Cl. 333—24)

This invention relates to unilateral transducers and more particularly to broad-band unilateral transducers for use in microwave transmission lines employing helical conductors.

A problem that has long existed in traveling-wave tubes is that reflections of the propagating waves are created by mismatches in the microwave circuit of the tube. These reflected waves, if of sufficient amplitude, will cause the tube to break into oscillation, thus destroying its use as an amplifier. In order to reduce the amplitude of the reflected waves and to prevent the tube from oscillating, it has been the practice in the past to introduce a lossy material into the microwave circuit of the tube. This method has been successful to prevent the tube from oscillating. However, because the lossy material is a bilateral attenuator, that is, it attenuates waves traveling in the forward direction as well as in the reverse direction, the gain of the traveling-wave amplifier is reduced.

The development of unilateral attenuators employing ferrite materials biased to gyromagnetic resonance has led to the use of such devices in traveling-wave amplifiers to overcome the above-mentioned problem. Such devices are described in articles by J. S. Cook, R. Kompfner, and H. Suhl, entitled "Nonreciprocal Loss in Traveling-Wave Tubes Using Ferrite Attenuators," page 1188, Proceedings of the IRE, July 1954, and by J. A. Rich and S. E. Webber, entitled "Ferrite Attenuators in Helices," page 100, Proceedings of the IRE, January 1955. Such devices permit the passage of the forward amplified waves in the traveling-wave amplifier with a negligible amount of attenuation, but greatly attenuate the reflected waves, thus preventing oscillations from building up.

A traveling-wave amplifier is an extremely broad-band device; this feature often constituting an important factor in its use in a microwave system. However, known unilateral ferrite attenuators, or isolators employed with traveling-wave amplifiers are not broad-band devices. This has the effect of limiting the useful bandwith of the traveling-wave amplifier to the bandwith of the ferrite isolator.

Therefore, it is an object of this invention to provide an improved unilateral transducer.

Another object of this invention is to provide a broad-band ferrite isolator for use in traveling-wave amplifiers.

Another object of this invention is to provide a broad-band unilateral attenuator for use in microwave transmission lines employing a helical conductor.

These and other objects which will become more apparent as the description proceeds are achieved by providing a ferrite element placed adjacent a helical transmission line in the region where the magnetic field of the microwave energy propagating on the transmission line is circularly polarized. To achieve broadbanding effects the ferrite element may take the form of a helix having a pitch which varies along its length, or along a portion of its length. The ferrite helix is placed about the R.F. transmission line. Alternatively, the helix pitch may be constant and the cross-sectional configuration of the ferrite material forming the helix may vary.

In another embodiment of this invention the ferrite element may be comprised of a plurality of ferrite rings placed about the helical transmission line and located at spaced regions along the transmission line. The ratio of the differential radius to the length of the individual rings being different at the different spaced regions along the transmission line.

In still another embodiment of the invention the ferrite element may take the form of a cylindrical tube disposed about the transmission line and extending in a direction parallel to the longitudinal axis of the transmission line; the differential radius of the ferrite tube being different at spaced regions along its length.

A further embodiment of the ferrite element may be comprised of a plurality of regions extending parallel to the axis of the transmission line; the ferrite material in each of said regions having a different saturation magnetization.

For a better understanding of the invention, reference is made to the accompanying drawings wherein:

Fig. 1 is a diagrammatic representation of the R.F. magnetic field on a helical transmission line;

Fig. 2 is a diagrammatic representation illustrating the internal magnetization of ferrite elements having different shapes;

Fig. 3 is a series of diagrams of various ferrite configurations useful in explaining the theory of operation of this invention;

Fig. 4 is a cross-sectional representation of one embodiment of the present invention; and

Figs. 5, 6, 7, and 8 are cross-sectional representations showing ferrite elements employed in alternative embodiments of this invention.

The theory of operation of microwave unilateral attenuators utilizing the gyromagnetic resonance phenomenon in a ferrite element is now well known in the art and may be briefly summarized as follows: if an R.F. magnetic field is circularly polarized in the positive sense in a plane perpendicular to the steady magnetization of a ferrite element, a large absorption of the microwave energy occurs at the value of the magnetizing field which brings the ferrite element into gyromagnetic resonance. This absorption of microwave energy does not occur when the R.F. magnetic field is circularly polarized in the negative sense.

Circular polarization is of the positive sense when the R.F. magnetic field rotates in a clockwise direction when viewed in the direction of the steady magnetization of the ferrite.

The above-cited articles point out that the R.F. magnetic field on a helical conductor is essentially circularly polarized in a thin region on the outside of the helix and that by placing ferrite rings, or a helical shaped ferrite element around the helical transmission line of a traveling-wave tube, and utilizing the magnetic focusing field of the traveling-wave amplifier as the ferrite magnetic biasing field, unilateral attenuation can be achieved.

By analyzing the expressions for the components of the magnetic field around a helical transmission line, as expressed on page 231 of "Traveling Wave Tubes," by J. R. Pierce, published by D. Van Nostrand Co., Inc., 1950, J. A. Rich and S. E. Webber have shown in the above-cited article that the magnetic field may be considered as essentially circularly polarized in the r—θ plane and in the r—z plane, where r, θ, and z are the radial, circumferential, and axial directions, respectively, of the helix.

The representation of the R.F. magnetic field around a helical transmission line as shown in Fig. 1 will aid in demonstrating this fact. Considering that propagation

of the microwave energy is from left to right, the projection of the magnetic vector A onto the r—z plane will show circular polarization of the magnetic field. The circular polarization is of one sense, positive or negative, on the outside of the helix, and of the opposite sense on the inside of the helix. For propagation of microwave energy from right to left, the sense of circular polarization, positive or negative, will be reversed. Also, the projection of the vector onto the r—θ plane will show circular polarization. In order to visualize this latter circular polarization it must be realized that because of the pitch of the helix, the true representation of the magnetic field is not parallel to the plane of the paper but is at an angle with the plane of the paper.

As pointed out above, in order to achieve unilateral attenuation employing the gyromagnetic resonance phenomenon the ferrite material must have a steady magnetization in a direction perpendicular to the plane of R.F. circular polarization, and this steady magnetization must be sufficient to bring the ferrite into resonance at the frequency of operation.

The steady internal magnetic fields present in several ferrite elements having different physical configurations will next be considered in connection with Fig. 2. In Fig. 2*a* is shown a ring of ferrite material positioned so that the applied steady magnetic field H_a is along the center axis of the ring. In this instance the ring of ferrite material will be magnetized in the z direction only and there will be no θ component, assuming that the ferrite material is homogeneous and that the applied field is along the center axis of the ring. Similarly, in Fig. 2*b*, where a tube of ferrite material is positioned so that the applied steady magnetic field is along its center axis, the ferrite material will be magnetized in the z direction only and will have no θ component of internal magnetization. A ferrite element in the form of a helix is shown in Fig. 2*c*. In this case, because of the high permeability of the ferrite material relative to the air gap between turns of the helix, the internal magnetization of the ferrite will be along the pitch of the helix. The steady internal magnetic field, H_{INT} may be considered as made up of a θ component and z component. In a helix with a moderate pitch angle ψ, the θ component will be predominant, so that in the discussion to follow hereinafter dealing with a ferrite helix having a moderate pitch angle, only θ component of steady magnetic field need be considered.

In considering the illustrations of Fig. 2, it can be seen that if the pitch angle ψ of the helix is appreciably increased, the z component of the internal magnetic field will increase since the pitch of the helix will be more closely aligned in the z direction. Likewise, if the pitch angle ψ is near zero, the θ component will diminish and the z component will be predominant. Thus by varying the pitch angle of the helix, the steady internal magnetic field, hence the magnetization of the ferrite may be varied.

C. Kittel in an article "On the Theory of Ferromagnetic Resonance Absorption," Physical Review, volume 73, No. 2, January 15, 1948, pages 155–161, has shown that the gyromagnetic resonant frequency is dependent on the shape of the ferrite specimen. This dependency is related to the nature of the demagnetizing fields, which in turn depends on the shape of the specimen. The general case of magnetic resonant frequency is thus given by

$$\omega_0=\gamma\{[H_a+(N_y-N_z)M_s]\times[H_a+(N_x-N_z)M_s]\}^{1/2} \quad (1)$$

where $\omega_0=2\pi f_0$ and f_0 is the gyromagnetic resonant frequency, γ is the magneto-mechanical ratio for an electron spin

$$\frac{\gamma}{2\pi}=2.80\frac{\text{mc.}}{\text{oersted}}$$

and H_a is the value of the steady magnetic field which is always directed in the z direction for purposes of this equation. The z direction in this equation corresponds to a direction perpendicular to the plane of the R.F. magnetic field circular polarization; N_x, N_y, N_z are the demagnetizing factors, the sum of which equals 4π, and M_s is the saturation magnetization of the ferrite, and depends on the ferrite composition.

Upon applying Equation 1 to various geometrical configurations of ferrite materials, the change in gyromagnetic resonant frequency may be illustrated. In Fig. 3, wherein H_a represents the applied steady magnetic field, two geometrical configurations are illustrated. In Fig. 3*a*, the steady magnetic field is applied parallel to the axis of a long, thin rod whose diameter is small compared to a wavelength in the ferrite medium. For this configuration and direction of applied field, $N_x=N_y=2\pi$; $N_z=0$, and

$$\omega_0=\gamma[H_a+2M_s] \quad (2)$$

In Fig. 3*b*, the steady magnetic field is applied transversely to the axis of the rod. For this situation $N_x=N_z=2\pi$; $N_y=0$, and

$$\omega_0=\gamma[H_a(H_a-2\pi M_s)]^{1/2} \quad (3)$$

In Fig. 3*c*, a thin ferrite slab is used, in which the slab thickness is small compared to a wavelength in the ferrite, and to the width and length of the ferrite samples. The magnetic field is applied perpendicularly to a narrow edge of the slab. For this case, $N_y=N_z=0$; $N_x=4\pi$, and

$$\omega_0=\gamma[H_a(H_a+4\pi M_s)]^{1/2} \quad (4)$$

In Fig. 3*d*, the static magnetic field is applied perpendicularly to the face of a thin ferrite slab. For this situation, $N_x=N_y=0$; $N_z=4\pi$, and

$$\omega_0=\gamma[H_a-4\pi M_s] \quad (5)$$

Thus it is seen that for a given ferrite material, specimens having different geometrical configurations may have different gyromagnetic frequencies. These equations also show that different values of steady magnetic field and different values of saturation magnetization result in different gyromagnetic resonant frequencies.

A device constructed in accordance with the present invention which will achieve broad-band unilateral attenuation is shown in diagrammatic form in Fig. 4 wherein the slow wave propagating structure of a traveling-wave tube is shown as a helical transmission line **11** enclosed within a glass envelope **12**. Disposed about the helical transmission line and glass envelope **12** and extending in a direction parallel to the longitudinal axis of transmission line **11** is a ferrite element **13** having the form of a helix. As is shown in Fig. 4, the cross-sectional configuration of the ferrite material forming the helix varies from a rectangle **40** having its major axis parallel to the longitudinal axis of the helical transmission line to a rectangle **42** having its major axis perpendicular to the longitudinal axis of the transmission line.

Enclosing the helical transmission line **11**, glass envelope **12**, and ferrite helix **13** is an envelope **14** which may be either metal or glass; members **18** and **19** represent conventional electron gun and collector electrodes, respectively, of a traveling-wave tube.

Waveguide **15** provides an input for the R.F. energy which couples to helical transmission line **11**. Waveguide **16** provides an output for the amplified R.F. energy. Focusing coil **17** surrounds the envelope **14** and provides a longitudinal magnetic field for focusing the electron beam of the traveling-wave tube, and also provides the applied steady magnetic biasing field H_a for the ferrite element **13**.

It is to be understood that the cross-sectional configuration of the ferrite material forming helix **13** may vary in such a manner that the cross-sectional area will take a form other than a rectangle. For instance, the cross-section may vary such that it is substantially tri-

angular in shape over a portion of the length of the helix, or it may be substantially circular over a portion of its length. Any of a number of diverse cross-sectional configurations may be employed, and indeed may have to be employed to obtain a desired bandwidth.

An alternative embodiment of a ferrite helix is shown in Fig. 5 where the ferrite material forming helix **13** has a substantially constant rectangular cross-section but the pitch of the helix varies along its length.

Both of the above-described embodiments of a ferrite helix disposed about the helical transmission line will provide broad-band attenuation of the reflected R.F. wave as will now be explained.

As was shown in connection with Fig. 1, circular polarization of the R.F. magnetic field exists in the r—z plane and in the r—θ plane. Also, the steady internal magnetic field which is established in the ferrite helix by the axial magnetic field has a θ component and a z component. As stated above, in the case of a ferrite helix of constant, moderate pitch, such as shown in Fig. 4, only the θ component of steady magnetic field need be considered. Therefore, the R.F. magnetic field circular polarization in the r—z plane and the θ component of steady magnetic field will be considered for this explanation relating to a ferrite element in the form of a helix.

Therefore, with these conditions present, and with the applied steady magnetic field in the direction shown in Fig. 4 and with the propagation of microwave energy from left to right, the R.F. magnetic field will be circularly polarized in a negative sense on the outside of helix **11** in the region where ferrite helix **13** is located. Under these conditions the forward amplified microwave will pass along the transmission line substantially unattenuated by the ferrite helix, but the reflected wave will be greatly attenuated since the reflected wave propagates from right to left and the R.F. magnetic on the outside of the helix **11** is then circularly polarized in a positive sense.

Referring to Fig. 4, the cross-section of the material forming the ferrite helix at cross-sectional area **40** is substantially a rectangle having its major axis parallel to the longitudinal axis of helix **11** and simulates a flat slab immersed in a steady magnetic field directed perpendicularly to a narrow edge as in Fig. 3*c*. As explained above, the gyromagnetic resonant frequency is expressed as in Equation 4 by

$$\omega_0=\gamma[H_\theta(H_\theta+4\pi M_s)]^{1/2}$$

In this expression H_θ is employed rather than H_a since it is the θ component of the steady magnetic field generated in the helix by the axial magnetic field which is used to bias the ferrite to the proper field to obtain unilateral attenuation.

At cross-sectional area **41** the material forming the ferrite helix can be considered as a thin, infinitely long rod immersed in a steady magnetic field parallel to the longitudinal axis of the rod, as in Fig. 3*a*. In this case the gyromagnetic resonant frequency is expressed as in Equation 2 by

$$\omega_0=\gamma[H_\theta+2\pi M_s]$$

At cross-sectional area **42** the material forming the ferrite helix may again be considered as a thin slab immersed in a steady magnetic field directed perpendicularly to a narrow edge, whose gyromagnetic resonant frequency is again expressed by Equation 4. Because the ferrite element **13** is comprised of a plurality of regions having different cross-sectional configurations, and since these configurations have different gyromagnetic resonant frequencies, broad-band unilateral attenuation will be achieved.

As shown in Fig. 5, the cross-sectional configuration of the ferrite helix **13** is substantially square and is constant throughout its length, but the pitch angle ψ of the

helix varies along its length. The helix in this case simulates a long, thin rod magnetized in a direction parallel to its longitudinal axis, as shown in Fig. 3*a*. The gyromagnetic resonance frequency for this configuration is expressed by Equation 2 by

$$\omega_0=\gamma[H_\theta+2\pi M_s]$$

As was pointed out in connection with Fig. 2, the steady internal magnetization of the ferrite will vary as the pitch angle ψ is varied. Thus, the H_θ term in the above equation will vary as the pitch angle is varied, and consequently the gyromagnetic resonant frequency of the ferrite of Fig. 5 element will be different at different regions along its length, and a broadbanding effect is achieved.

Another means for obtaining attenuation of the reflected wave over a broad band of frequencies is shown in Fig. 6. In this embodiment the ferrite element is comprised of a plurality of ring-shaped members **18–22**, which are disposed around helical transmission **11** at spaced regions along its length. It may be seen that the ratio of the differential radius to the length of the individual ring-shaped members varies along the length of the transmission line. Differential radius is defined as the difference in length between the inside radius and the outside radius of a ring-shaped member.

In member **18** the differential radius is small compared to the length of the member, while in member **20** the differential radius is large compared to its length. In member **19** the differential radius and length are substantially equal.

In practice it may be desirable to employ a ferrite element comprised of more or less ring-shaped members than are shown in Fig. 6; five members are shown merely for purposes of illustration.

A broad-band unilateral transducer or isolator constructed in accordance with this invention may take still another form, and is illustrated in Fig. 7. In this embodiment, the ferrite element **13** disposed about helical transmission line **11** is in the form of a tube which extends parallel to the axis of transmission line **11**. It may be seen that a spaced regions along the length of the tube the differential radius of the tube is different.

As discussed in connection with Fig. 2, with the steady magnetic field applied in the direction shown in that figure, the steady magnetization of the ferrite ring and tube is in the z direction only. Therefore, in Figs. 6 and 7, circular polarization of the R.F. magnetic field in the r—θ plane, and the steady magnetization of the ferrite element in the z direction are the components which produce gyromagnetic resonance in the ferrite element.

In Fig. 6 the individual rings can be considered approximately as either rods or sheets of ferrite material infinite in extent, depending upon the ratio of the ring length to differential radius. In ferrite ring **18** the length of the ring is large compared with its differential radius and simulates a flat slab of ferrite material immersed in a steady magnetic field directed perpendicularly to a narrow edge. For this configuration the gyromagnetic resonant frequency is expressed in Equation 4 by

$$\omega_0=\gamma[H_a(H_a+4\pi M_s)]^{1/2}$$

In ring **19** the differential radius is substantially equal to the length of the ring and simulates a ferrite rod immersed in a steady magnetic field perpendicular to its longitudinal axis and the gyromagnetic resonant frequency is expressed as in Equation 3 by

$$\omega_0=\gamma[H_a(H_a-2\pi M_s)]^{1/2}$$

In ring **20** the differential radius of the ring is large compared with the length of the ring and simulates a thin slab of ferrite material magnetized perpendicularly to its broad face, and the gyromagnetic resonant frequency is expressed by Equation 5 as

$$\omega_0=\gamma[H_a-4\pi M_s]$$

Again it is evident that absorption of the microwave energy will occur over a broad band of frequencies as expressed by the above equations.

The analogy made with the rings of Fig. 6 may also be made with respect to the tube of ferrite shown in Fig. 7 by considering that the tube is comprised of a plurality of regions spaced along its length. These regions, when considered individually, will be similar to the individual rings of Fig. 6 and broad-band unilateral attenuation will also be achieved.

It should be noted that the ferrite tube of Fig. 7 may have the effect of concentrating the applied magnetic field (the electron beam focusing field) within the ferrite tube, thus resulting in a defocusing of the electron beam of the traveling-wave tube. For this reason the ferrite element is preferably made in the form of rings or a helix in which case the above-noted difficulty is largely eliminated.

However, if a suitable ferrite material with a relatively low D.C. permeability is employed in the ferrite tube, the concentration of the magnetic field in the ferrite element may be reduced and objectionable defocusing of the electron beam may be reduced to an acceptable level.

The above equations also indicate that different values of M_s will result in different gyromagnetic resonant frequencies. Thus the physical configuration of the ferrite element may be maintained constant and a plurality of ferrite materials having different saturation magnetizations may be employed to obtain broad-band unilateral attenuation. For instance, in Fig. 4, the ferrite element may be comprised of a plurality of ferrite helices, each helix being made of ferrite material which has a different saturation magnetization. Likewise, in Fig. 6, the individual rings of Fig. 6 may be made of different ferrite materials. Thus a broad-band unilateral transducer may also be constructed by employing a ferrite element which is comprised of a plurality of regions having different saturation magnetizations.

It is known that as the frequency of the microwave energy increases, the R.F. wave is concentrated more closely to the helical transmission line. This causes the region of maximum circular polarization of the R.F. wave to move closer to the helical transmission line. To assure optimum interaction of the microwave energy and the ferrite element at the higher microwave frequencies, the ferrite element should be so constructed that at least a portion of it is located in the region of maximum circular polarization at the higher frequencies. A device constructed in accordance with this invention which will take this fact into account is illustrated in Fig. 8. The ferrite element is comprised of a plurality of ring-shaped members wherein the inner surface of ring **30** is closely adjacent the helical transmission line **11**, and the inner surfaces of rings **31**, **32**, and **33** are progressively further away from transmission line **11**. When the microwave frequency increases and the region of maximum circular polarization moves closer to the transmission line helix, there will always be a ferrite ring which is in position for optimum interaction with the R.F. wave.

For optimum performance of this device ring **30** would have a value of saturation magnetization which would cause it to be gyromagnetically resonant at a higher frequency, in which case the region of maximum circular polarization is close to the helix **11**. Similarly, rings **31**, **32**, and **33** would have values of saturation magnetization such that each would be gyromagnetically resonant at a progressively lower frequency since the region of maximum circular polarization will move further from helix **11** as the frequency decreases.

Broadbanding of the unilateral attenuator, or isolator, may be achieved by employing a combination of any of the above-discussed methods, and in some instances it may be necessary to rely on a combination of methods to achieve the desired bandwidth. For example, ferrite rings made of one ferrite material and a ferrite helix made of a different ferrite element may be employed.

The steady magnetization of the various ferrite elements described above may also be achieved by employing ferrite elements which are permanently magnetized, rather than utilizing the electron beam focusing field to provide the steady magnetization. In such a case the ring-shaped ferrite members and the tubular ferrite element may be magnetized in the θ direction or in the z direction. However, it is believed that it is preferable to use the previously-discussed method in a traveling-wave tube because the magnetic fields associated with the permanently magnetized ferrite element are likely to have a detrimental effect on the focusing of the electron beam in the tube.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than of limitation and that changes within the purview of the appended claims may be made without departing from the true scope and spirit of the invention in its broader aspects.

What is claimed is:

1. A unilateral transducer comprising a helical wire transmission line adapted to propagate waves of microwave energy in a given band of frequencies, the magnetic field of said waves being substantially circularly polarized in a region surrounding said transmission line, ferrite material disposed coaxially about said wire helix in a plurality of longitudinally spaced regions where the magnetic field of said waves is circularly polarized, the longitudinal dimensions of the ferrite progressively increasing throughout substantially the entire longitudinal extent of said spaced regions in a direction parallel to the longitudinal axis of the wire helix and the radial dimensions of the ferrite progressively decreasing throughout substantially the entire longitudinal extent of said spaced regions in the same direction parallel to the longitudinal axis of said wire helix, and means for immersing said ferrite in a steady magnetic field which is directed parallel to the longitudinal axis of said wire helix and of sufficient strength to magnetize the ferrite in each of said spaced regions to a different gyromagnetic resonant frequency which is included in the given band of frequencies.

2. The combination as claimed in claim 1 wherein said ferrite material is in the form of a helix and the longitudinal and radial dimensions of the individual convolutions of the ferrite helix in a plane parallel to the longitudinal axis vary in the manner described in claim 1.

3. The combination as claimed in claim 1 wherein said ferrite material is in the form of a plurality of longitudinally spaced rings and the lengths of the rings in the direction parallel to the longitudinal axis of the wire helix and the differential radii of the rings vary in the manner described in claim 1.

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