Jan. 23, 1951 E. FEENBERG 2,538,771

HIGH-FREQUENCY ATTENUATOR

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FIG. 1

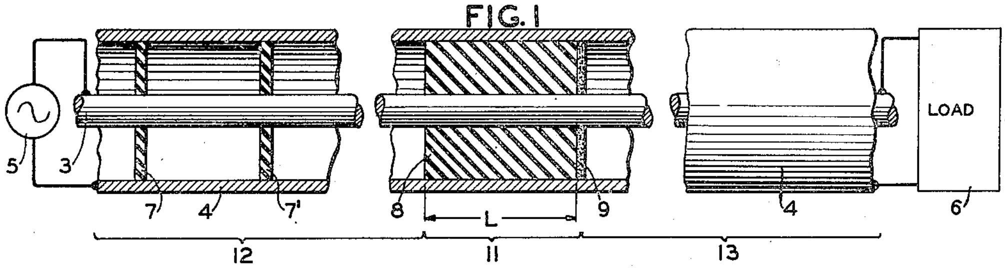

FIG. 2

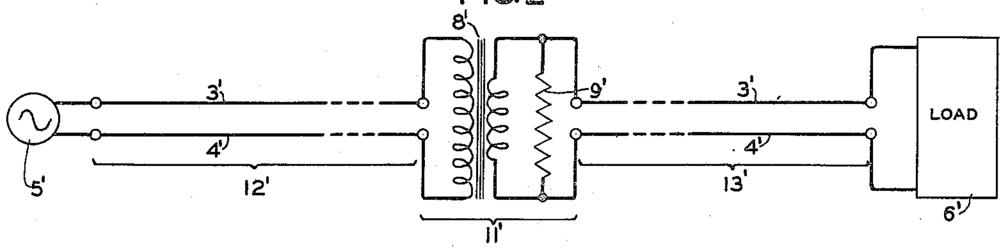

FIG. 3

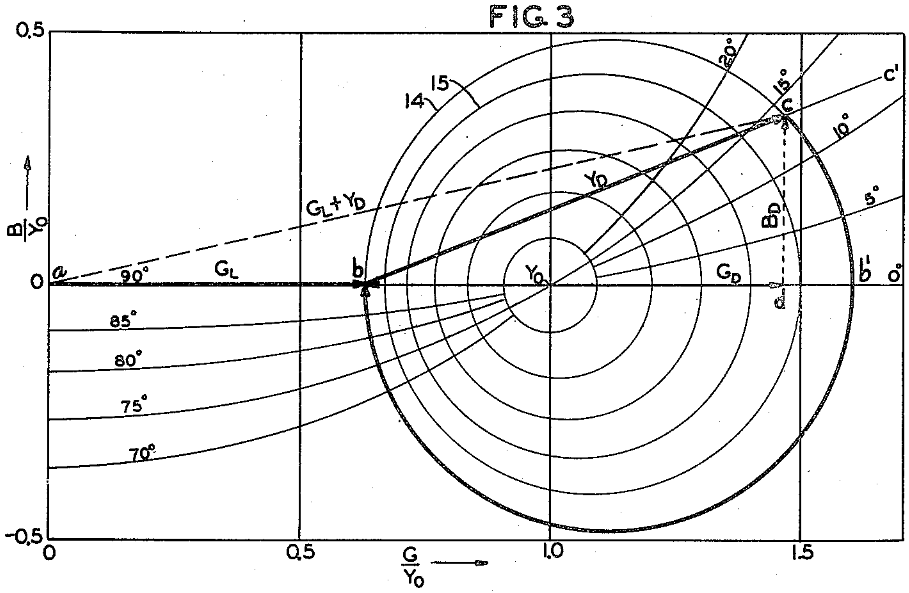

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FIG. 4

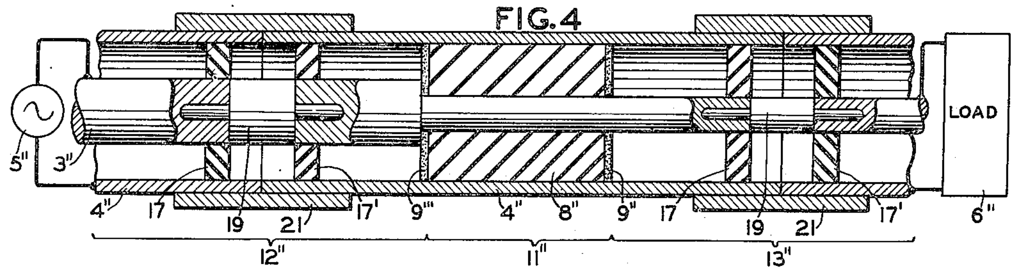

FIG. 6

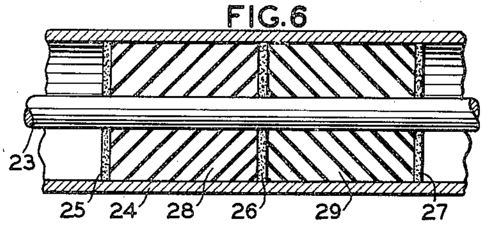

FIG. 10

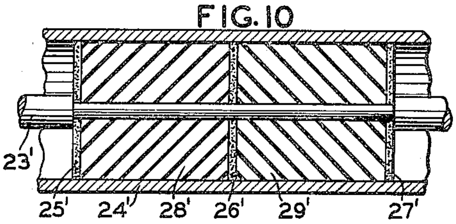

FIG. 8

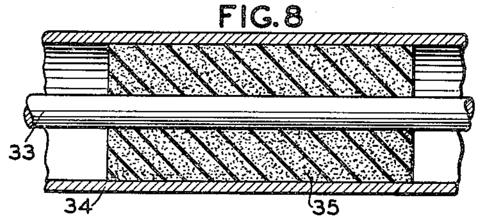

FIG. 11

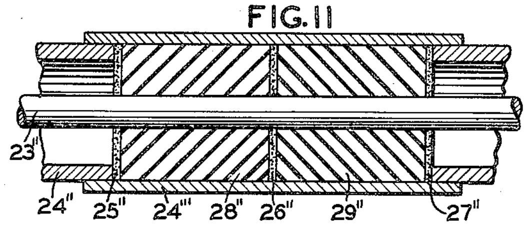

FIG. 9

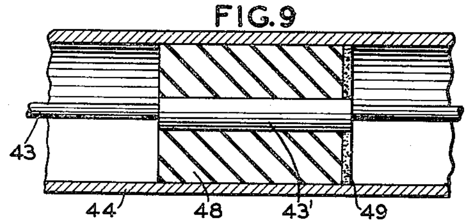

FIG. 12

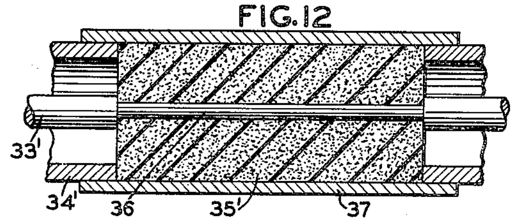

FIG. 14

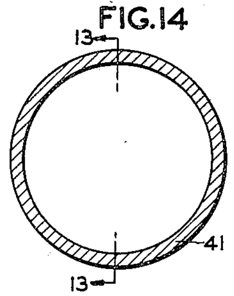

FIG. 13

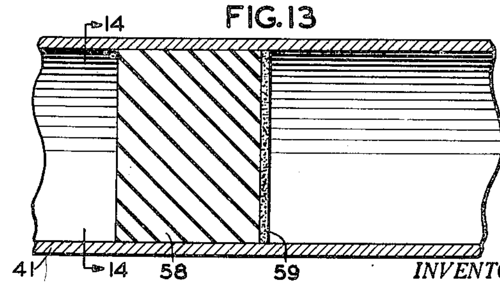

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FIG. 5

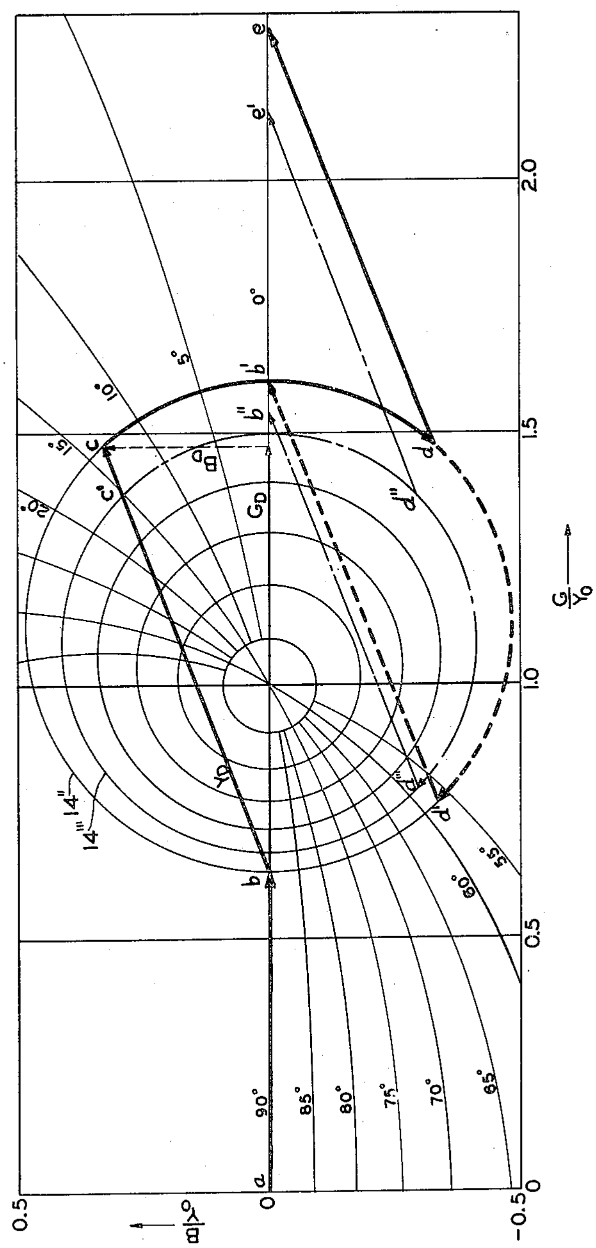

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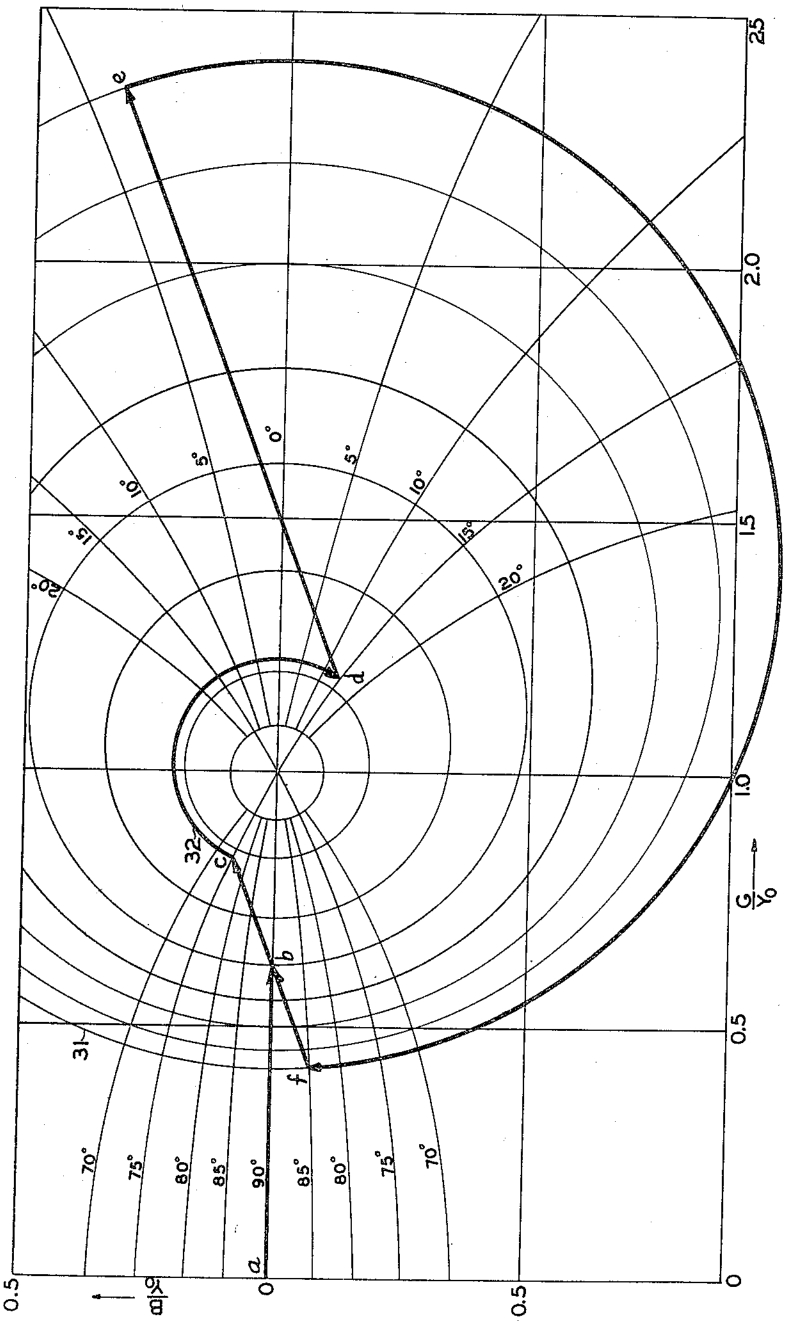
FIG. 7



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Patented Jan. 23, 1951

2,538,771

UNITED STATES PATENT OFFICE

2,538,771

HIGH-FREQUENCY ATTENUATOR

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Application August 2, 1944, Serial No. 547,774

7 Claims. (Cl. 178—44)

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The present invention relates to devices for attenuating high frequency electromagnetic energy, and especially to devices adapted for use within high frequency conductors such as coaxial transmission lines or wave guides.

In many high frequency electrical systems, it is necessary or desirable to attenuate by a predetermined amount the energy transmitted from one point to another. Usually such energy transmission is accomplished through a self-enclosed conductor, such as a hollow-pipe waveguide or a coaxial line, and it is often desirable that attenuating apparatus be especially designed to be inserted entirely within or made a part of such a high frequency conductor.

Usually considerable attention is given to the design of the self-enclosed high frequency conductors of the above-described types, as well as to the parts of a system linked together thereby, to achieve a condition of complete impedance match throughout the high frequency conductor. Accordingly, it is particularly desirable that an attenuator for use within such a conductor be so designed as to present a desired input impedance when terminated in a properly matched load.

In some cases, the attenuating device may be electrically asymmetrical, and care must be exercised in the orientation of the device with respect to the source and load ends of the transmission line to maintain a desired impedance match throughout. In other cases, it is desirable that a symmetrical attenuating device be provided so that the source and load ends of the transmission line incorporating the attenuating device may be interchanged or the attenuator orientation reversed without introducing a condition of impedance mis-match.

It is also desirable to provide an attenuator structure which is easy to manufacture and install, and which is sufficiently rugged mechanically to insure that the attenuating and impedance-matching characteristics of the device remain constant. The practicability of attenuator elements for use within a high frequency energy conductor depends to a great extent on the ease of mechanical adjustment of the dissipator sections therein. If very thin discs of semi-conductive material are required as the dissipators of a coaxial line attenuator, for example, and if these discs must be separated by air-dielectric transmission line sections of carefully predetermined length, it is often found that very tedious operations are required to achieve the proper positioning of the dissipator elements within the line. Also, rough handling of the transmission line so

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constructed, or prolonged vibration thereof, may result in a shift of position of such dissipator discs or even in breakage of the discs, changing the characteristics of the attenuator and thus seriously impairing its performance.

In some forms of the present invention a solid dielectric body is inserted within the high frequency energy conductor to fill a section of the energy conductor of appreciable length. The dissipator element is attached to this solid dielectric body, and is mechanically supported and rigidly held in correct position by the dielectric body. The dissipator element either may be a preformed thin disc of compressed and bonded carbon particles, cemented to the end of the dielectric body, or it may be a layer of carbon-bearing paint applied to the end of the dielectric body and dried thereon. Other semi-conductive materials besides carbon may be used in the dissipator element, if desired. The solid dielectric body is of an appreciable length usually comparable with or greater than its diameter, and, being formed of a size adapted to fit snugly within the outer metallic portion of the hollow high frequency energy conductor, it serves not only to support the dissipator element but also to align it normal to the axis of the energy conductor.

The solid dielectric body for insertion within the high frequency energy conductor serves not only as a support for the dissipator element, as described above, but also as means for changing the characteristic admittance of the transmission line section filled by the dielectric body from the characteristic admittance with air-dielectric. Thus, the solid dielectric body is made to serve simultaneously as an important structural member and also as a vital admittance transformer member within the attenuator embodiments of the present invention. The admittance-transforming function of the dielectric body is particularly useful in rendering the input impedance of the attenuator substantially equal to the output or load impedance to which high frequency energy is delivered through the attenuator.

Furthermore, if the dissipator element is not purely resistive, but instead is characterized by appreciable reactance in addition to its resistance, the length of the solid dielectric body may be adjusted to compensate for this reactance, rendering the attenuator input impedance purely resistive.

Accordingly, it is an object of the present invention to provide improved high frequency attenuating devices incorporating special provision for matching the impedance of the attenuator to the impedances of the other devices connected thereto.

It is another object of the present invention to provide improved high frequency attenuating devices which are relatively easy to construct.

It is a further object of the present invention to provide improved high frequency attenuating devices which are mechanically rugged, so that constant characteristics of the devices may be maintained.

It is still another object of the present invention to provide improved attenuating devices which easily may be inserted directly within concentric line transmission systems.

It is still a further object of the present invention to provide improved attenuating devices which may be inserted within hollow pipe waveguide high frequency energy conductors.

It is yet a further object of the present invention to provide an improved attenuating device wherein a solid dielectric body is provided for energy dissipation distributed therethrough.

Other objects and advantages will become apparent from the specification taken in connection with the accompanying drawings wherein the invention is embodied in concrete form.

In the drawings:

Fig. 1 shows a longitudinal view, partly in section, of one form of attenuating device especially useful where a fixed small value of attenuation is desired, and where asymmetry of the attenuating device is permissible;

Fig. 2 shows an equivalent circuit diagram of the system of Fig. 1, showing the manner in which the attenuator of Fig. 1 is inserted in a transmission line between a source of high frequency energy and a load matched to said transmission line without altering the impedance presented to said source;

Fig. 3 is an admittance diagram useful in explaining the theory of operation of the device of Fig. 1;

Fig. 4 shows a longitudinal cross-sectional view of an attenuating device characterized by symmetrical arrangement of elements, and further characterized by an impedance transformation to a relatively high input admittance;

Fig. 5 is an admittance diagram useful in explaining the theory of operation of the device of Fig. 4;

Fig. 6 shows a longitudinal cross-sectional view of a form of attenuating device employing three dissipative elements separated by solid dielectric "beads" or bodies; the attenuating device of Fig. 6 being characterized by symmetry and further characterized by input admittance equal to the load admittance;

Fig. 7 is an admittance diagram useful in explaining the theory of operation of the device of Fig. 6;

Fig. 8 shows a longitudinal cross-sectional view of a further form of attenuating device wherein the energy dissipating material may be dispersed throughout a solid dielectric body, or a normally high loss dielectric material may be employed, so that the dissipation is distributed throughout the solid dielectric body of the attenuating device;

Fig. 9 shows a longitudinal cross-sectional view of an attenuator similar to that of Fig. 1, but with a larger diameter inner conductor extending throughout the length of the solid dielectric body of the attenuating device;

Fig. 10 shows a longitudinal cross-sectional view of an attenuating device similar to that of Fig. 6 wherein a reduced inner conductor diameter is employed throughout the axial extent of the solid dielectric bodies;

Fig. 11 shows a longitudinal cross-sectional view of an attenuating device somewhat similar to that of Fig. 6, wherein the outer conductor diameter is increased throughout the axial extent of the solid dielectric bodies;

Fig. 12 shows an attenuating device generally similar to that shown in Fig. 8, but with the inner conductor diameter decreased and the outer conductor diameter increased throughout the axial extent of the high-loss solid dielectric material;

Fig. 13 shows an attenuator generally similar to that of Fig. 1 adapted to a circular cross-section hollow pipe waveguide; and

Fig. 14 is a cross-sectional view taken along the line 14—14 of Fig. 13.

Referring now to the drawings:

Fig. 1 shows a concentric or coaxial transmission line having an inner conductor **3** and outer conductor **4** extending between a source of high frequency energy **5** and a high frequency load **6**. The inner conductor **3** and outer conductor **4** of the concentric transmission line may be generally separated by air dielectric, with pairs of thin solid dielectric discs **7**, **7'** inserted at suitable points along said line for providing rigid mechanical positioning of inner conductor **3** with respect to outer conductor **4**. The two spacers of each pair are separated by substantially a quarter wavelength at the operating frequency of source **5**, so as to provide cancellation of reflections produced by the spacers of each pair. The characteristic impedance of the air-dielectric transmission line **3**, **4** is matched to the impedance of load **6**.

A simple attenuator may be made within a section **11** of transmission line **3**, **4**, as shown in Fig. 1. A dielectric body **8** and a dissipator disc **9** are positioned within the hollow outer conductor **4** of the concentric transmission line. The dissipator disc **9** is composed of suitable semi-conductive material to provide a dissipative current conduction path shunting the load **6**. Part of the energy delivered through the concentric transmission line **3**, **4** from source **5** is dissipated in the semi-conductive disc **9**, while the remaining energy from source **5** is delivered to load **6**.

The dielectric body **8** in this embodiment of the present invention performs two important functions in relation to dissipative disc or layer **9**. First, the dielectric body **8** having an appreciable length L, serves as an excellent mechanical means for rigidly aligning semi-conductive disc **9** perpendicularly within the concentric line 3, 4. Also, the dielectric body **8** in juxtaposition to the semi-conductive surface layer **9** cooperates with inner and outer conductors **3** and **4** to form a solid dielectric filled transmission line section **11** having a different characteristic impedance from that of the air-filled transmission line section **12** extending to source **5** and the air-filled section **13** extending to the load **6**. This solid dielectric-filled transmission line section thus serves as an impedance transformer, the effect of which may be varied over a wide range by variation of its length L.

By virtue of this impedance transformer section, an appreciable loss may be inserted by the attenuator without introduction of an impedance mismatch at the input end of the attenuator adjacent the transmission line section **12**. Suppose, for example, that the impedance of load 6 is 100 ohms resistance and that the characteristic impedance Z_0 of the air-dielectric sections 12 and 13 of transmission line 3, 4 is 100 ohms. Suppose further that 6 decibels relative attenuation is desired to be provided by the dissipator disc or layer 9, so that one-fourth of the input power is to be transferred to the load. Then the layer 9 should be a 33⅓-ohm resistance element. Acting in shunt with the 100-ohm resistance represented by the load 6 coupled through transmission line section 13, this 33⅓-ohm dissipator element 9 dissipates ¾ of the energy arriving from source 5, while one-fourth of this energy passes onward to load 6, as required.

Thus, the dissipator element 9 could function alone as a 6-decibel attenuator, if it were mechanically self-supporting, and if the impedance presented to the tranmission line section 12 were immaterial. The impedance presented to the transmission line section 12 extending to source 5 from the dissipator would be

$$\frac{1}{\frac{1}{33\frac{1}{3}}+\frac{1}{100}}$$

or 25 ohms resistance. Thus a serious condition of impedance mismatch and standing waves would be introduced in this air-dielectric section of transmission line having 100 ohms characteristic impedance. The impedance presented to source 5 might then vary over a 16:1 range, being any value between 25 ohms and 400 ohms, and might be partly reactive instead of purely resistive, depending on the length of the transmission line section 12 between the source and the dissipator.

The highly undesirable impedance mismatch produced by the introduction of dissipator 9 alone within the transmission line 3, 4 is entirely overcome in the present invention by the use of a dielectric body 8 of chosen characteristics and dimensions. The length L of the body 8 should be determined in accordance with the equation

$$L=\frac{\lambda}{4\sqrt{\epsilon}}$$

where λ is the free-space wavelength corresponding to the frequency of source 5, and ϵ is the dielectric constant of the body 8 and is determined by the relation

$$\epsilon=R_L\left(\frac{1}{R_L}+\frac{1}{R_D}\right)=1+\frac{R_L}{R_D}$$

where R_L is the resistance of the reactance-free load 5 and is equal to the characteristic impedance of the air-filled transmission line sections 12 and 13, and R_D is the resistance of the reactance-free dissipator 9.

For the above example of a 100-ohm load and air-filled line, with a 33⅓ ohm resistive dissipator for 6 decibels attenuation,

$$\epsilon=1+\frac{R_L}{R_D}=1+\frac{100}{33\frac{1}{3}}=4$$

and

$$L=\frac{\lambda}{4\sqrt{\epsilon}}=\frac{\lambda}{4\sqrt{4}}=\frac{\lambda}{8}$$

Thus, for a complete attenuator according to the above example for 6 decibels attenuation and a completely matched condition at a source frequency of 750 megacycles per second, for example, $\gamma=40$ cm., and $L=5$ cm. with a dielectric constant of 4. In this example, the characteristic impedance of transmission line section 11 is 50 ohms, as given by taking the quotient of the characteristic impedance of an air-filled section, 100 ohms, divided by $\sqrt{\epsilon}$. Also the effective electrical length of the solid dielectric body 8 in the above example is 90°, as given by

$$\frac{L\sqrt{\epsilon}}{\lambda}\times 360^\circ$$

Fig. 2 is an equivalent circuit diagram through which the operation of the foregoing transmission system and attenuator may be more clearly understood. An alternating-current source 5′ supplies energy to a 100-ohm resistive load 6′ through sections 12′ and 13′ of transmission line 3′, 4′ having a characteristic impedance of 100 ohms. A 33⅓-ohm resistor 9′ is connected across the transmission line 3′, 4′ so that the resultant impedance provided by the load 6′ through transmission line section 13′ and the dissipator 9′ connected across the line 3′, 4′ is 25 ohms.

A transformer 8′ having half as many turns in its secondary winding as in its primary winding for an impedance transformation ratio of 4:1 is introduced into the circuit with its secondary winding connected to the dissipator 9′ and its primary connected to transmission line section 12′. The impedance then presented by the primary winding of transformer 8′ to the source 5′ and the transmission line section 12′ is 100 ohms resistance. Therefore, the system impedances are properly matched, and no standing waves are present along the transmission line 3′, 4′.

In this equivalent circuit diagram, it is readily seen that if the positions of the source 5′ and the load 6′ were interchanged, the attenuator consisting of dissipator 9′ and transformer 8′ would not be suited for maintaining a condition of impedance match throughout the system. The 100-ohm load would then be connected across the 100-ohm winding of transformer 8′, and would produce a 25-ohm impedance in the opposite winding. The 33⅓-ohm dissipator 9′ connected in shunt with the 25-ohm transformer winding would result in a net impedance of 14.25 ohms, with a resultant impedance mismatch to transmission line section 13′ of approximately 7:1.

Through study of the equivalent circuit diagram of Fig. 2 which illustrates the cooperation of the dissipator 9 and the solid-dielectric filled impedance transformer section of transmission line adjacent dissipator 9, the operation of the coaxial-line attenuator may be clearly understood. It is thus made apparent that the attenuator of Fig. 1 must be properly oriented with respect to the load and source ends of the system in which it is employed, since impedance matching is effected for energy transmitted in only one direction.

In the above discussion, a purely resistive dissipator 9 is assumed. Actually, at very high frequencies, a dissipative disc or layer made up of compressed or deposited carbon particles is likely to have a complex impedance rather than a pure resistance. At a frequency of 3000 megacycles per second ($\lambda=10$ cm.), for example, certain samples of dissipator layers have been found to have appreciable capacitive reactance. For such a dissipator, the length L of the solid dielectric body 8 may be varied from the 90° effective electrical length as used in the above example, to provide compensation for the reactive component of impedance of dissipator 9.

Fig. 3 shows an admittance circle diagram useful for analysis of the more complicated matched-impedance attenuator wherein dissipator 9 has a complex impedance. Such circle diagrams are widely useful for simple graphical analysis of transmission line behavior. If a section of transmission line of uniform characteristic impedance is terminated in a load of equal impedance, a completely matched condition is achieved and the input impedance presented by the transmission line section is uniform and independent of its length. If on the other hand the transmission line section is terminated in an impedance different from its characteristic impedance, then the input impedance of the transmission line section varies between two limits as the length of the transmission line section varies. One of these limits is the termination impedance, and the other is given as the quotient of the square of the characteristic impedance of the section divided by the termination impedance. The input impedance alternates between these limits at space intervals of 90° electrical phase difference, and at intermediate lengths, varies through regions of complex impedance, first capacitive and then inductive.

A circle diagram of the type shown in Figs. 3, 5 and 7 may be used for analysis of the variation of impedance (or admittance) of a transmission line section with respect to the length of the section and the ratio of the termination impedance or admittance) to the characteristic impedance (or admittance) of the transmission line section. In such a diagram, as used for admittance analysis, the abscissae represent conductance values and the ordinates represent susceptance values. For study of these admittance components, the rectangular coordinate graph is provided. A series of circles having centers on the axis of abscissae are superimposed on the rectangular coordinate graph. Each such circle passes through points of reciprocal abscissae on the axis of abscissae.

For example, a circle 15 passes through reciprocal points (0.667,0) and (1.5,0). This circle represents the variation of input admittance—input conductance and input susceptance—with respect to the variation of length of a transmission line section of admittance Y_0 and termination of conductance $G=\frac{2}{3}Y_0$ or $G=\frac{3}{2}Y_0$. The input admittance of such a line section varies clockwise along curve 15 as the length of the line section between the termination and the input point considered is increased. For an air dielectric line, the input impedance varies between the above two limits over a length of $\lambda/4$, making a complete cycle of variation around circle 15 from one limit to the other and return in a length of $\lambda/2$, where λ is the free-space wavelength of the energy transmitted through the transmission line. Graph paper suitable for use in such analyses is supplied by the Keuffel and Esser Co. of New York, under the type designation 369-14. In order to make use of such a diagram for the present purpose it is convenient to consider the characteristics of the circuit elements in terms of admittance Y, susceptance B, and conductance G rather than impedance, reactance and resistance. The ordinate axis of Fig. 3 represents the ratio B/Y_0 of susceptance B to the characteristic admittance

$$Y_0\left(=\frac{1}{Z_0}\right)$$

of solid-dielectric filled line section 11, while the abscissa axis represents the ratio G/Y_0 of conductance G to characteristic admittance Y_0.

Furthermore, the computation by use of the circle admittance diagram for a desired attenuator unit is simplified if a predetermined dielectric material is first chosen for the body 8. The example illustrated in Fig. 3 is based on a body 8 of polystyrene, for which the dielectric constant $\epsilon=2.56$, at $\lambda=10$ centimeters. The dissipator 9 in this case is characterized by a ratio of reactance to resistance of 0.4, defining an admittance angle of 21.8°. The point b in Fig. 3 is then located for ordinate 0 and

$$\text{abscissa}=\frac{1}{\sqrt{\epsilon}}=\frac{1}{1.6}=0.625$$

The vector ab then represents conductance G_L of load 6 (equal to the characteristic admittance of air-filled transmission line sections 12 and 13), in relation to the characteristic admittance Y_0 of the section 11 of transmission line of conductor dimensions equal to those of sections 12 and 13 but of solid dielectric 8 characterized by the dielectric constant $\epsilon=2.56$.

The dissipator element 9 is effectively in shunt with the load G_L presented through the transmission line section 13, and so a vector representing the admittance Y_D of the dissipator 9 must be added directly to the vector ab to produce the resultant admittance of load plus dissipator. The magnitude of the vector Y_D is to be determined from the circle diagram of Fig. 3, but the line bc' along which the vector must lie is known to have a slope of 21.8°. Now, a circle 14 having a diameter b, b' extending between the point b of coordinates (0.625, 0) and the point b' of coordinates

$$\left(\frac{1}{0.625}, 0\right)$$

is drawn in the diagram of Fig. 3. The intersection c of the circle 14 and the line bc' is then located as the terminus of the vector bc representing the admittance Y_D of dissipator 9 for which the polystyrene-filled transmission line section 11 is capable of providing an admittance at the input end thereof equal to the conductive admittance G_L of load 6.

The phase angle calibration circles passing through the point (1.0, 0) and having centers on the axis of ordinates then provide a measure of the effective electrical length of the polystyrene body 8. This length is seen in Fig. 3 to be 104° of which a portion of 14° length is effective to compensate for the capacitive susceptance B_D of dissipator 9 and the remaining effective 90° length section serves as an admittance transformer as described above for rendering the admittance at the input end of attenuator section 11 equal to the load conductance G_L.

Thus, the diagram of Fig. 3 includes two admittance vectors G_L and Y_D added to define a point c having the rectangular coordinates (1.46, 0.33) representing the sum of the shunt admittances of load 6 and dissipator 9 in relation to the characteristic admittance 1.0, 0 of the polystyrene-filled section of the transmission line 3, 4. From the point c an arc of the circle 14 passing through b' and b, points of reciprocal abscissae, proceeds in a clockwise direction to terminate at point b, representing a transformation effected by line section 11 from the large complex admittance ac at the dissipator element 9 to the desired conductive input admittance ab

at the input end of transmission line section 11.

With the phase angle of admittance of dissipator 9 fixed, and with polystyrene chosen as the material for solid dielectric body 8 for insection in the transmission line of uniform diameter conductors 3 and 4, a unique solution is thus obtained for the length of body 8 and the admittance of dissipator element 9. By comparison of the conductance G_L of load 6 with the sum of the conductive component G_D of the admittance Y_D of dissipator 9 (shown as *bd* in Fig. 3) added to G_L, the ratio of the energy passed to load 6 to the total energy received is obtained, and thus the relative attenuation of the transmission line section 11 may be determined. For the above example, this found to be

$$\frac{G_L}{G_L+G_D}=\frac{0.625}{0.625+0.84}=.426$$

corresponding to 3.7 decibels attenuation in section 11.

It is readily seen that any desired number of composite attenuator units similar to that comprising the dielectric body 8 and the attached attenuator element 9 may be used in cascade within the transmission line 3, 4 for any integral multiple of 3.7 decibels attenuation, without departure from the desired condition of input admittance equal to the conductance G_L of load 6.

Fig. 4 shows a high frequency energy transmission system embodying a symmetrical attenuator unit which presents a much lower input impedance than the load impedance to which energy is supplied through the attentuator. This system comprises a load 6'' supplied with high frequency energy by source 5'' through coaxial transmission line 3'', 4''. If the characteristic admittance of the air-dielectric section 12'' of the transmission line 3'', 4'' is much greater than the conductance of load 6'' and the equal characteristic admittance of the air-dielectric section 13'' of transmission line 3'', 4'', then the solid dielectric body 8'' may be used to support a dissipator 9'' at the load end and an equal dissipator 9''' at the source end. The dielectric body 8'' may be made of such length as to serve only for compensating for the susceptance components introduced by dissipators 9'' and 9''', or the body 8'' may be made sufficiently longer to provide an admittance transformation effect as well.

The admittance diagram of Fig. 5 illustrates the above two alternative ways in which the attenuator of Fig. 4 may be made to operate. As before, polystyrene is taken as the material for the solid dielectric body, 8''. From the dielectric constant $\epsilon=2.56$, $\sqrt{\epsilon}=1.6$, and thus the reciprocal abscissa points *b* and *b'* on this diagram are fixed for the diameters of conductors 3'' and 4'' in the polystyrene dielectric section 11'' equal to those in the air-filled section 13'' extending to load 6''. The circle 14'', and the location and extent of vector *bc*, are illustrated for a dissipator 9'' equal to that illustrated by the generally similar admittance diagram of Fig. 3.

If a very large input admittance is to be presented by the attenuator section 11'' of the transmission line 3'', 4'', the effective electrical length of the polystyrene body 8'' may be made 2×14°, as indicated by arc *cd* of Fig. 4, the essential condition being that point *d* shall have the same conductance as point *c*, and equal magnitude susceptance of opposite sign. Then the admittance added by dissipator 9''' is represented by vector *de*, resulting in an input admittance equal to G_L+2G_D, where G_L is the conductance of load 6'' and G_D is equal to the conductive component of each of the equal dissipators 9'' and 9'''.

If a somewhat smaller input admittance than that defined above is desired, the effective electrical length of the solid dielectric body 8'' may be made 14°+57°, or 71°, as illustrated by the arc *cdd'* in Fig. 5, the essential condition being here that point *d'* have susceptance of equal magnitude to that of point *d*. At 3000 megacycles per second, corresponding to $\lambda=10$ centimeters, and with $\sqrt{\epsilon}=1.6$ for polystyrene, the length of the body 8'' is thus given as

$$L=\frac{71}{360}\times\frac{10}{1.6},\text{ or }1.23\text{ cm.}$$

With this length of the body 8'', dotted vector *d'b'* of Fig. 5 representing the admittance of dissipator 9''', added to the admittance produced through the transformation effect within the solid-dielectric transmission line section, results in an input admittance *ab'*, which is equal to ϵG_L, which for polystyrene dielectric material 8''' is equal to $2.56G_L$.

It should be noted that for the structure of Fig. 4, unlike that of Fig. 1, there is no special significance in terminating the vector *bc* on the circle 14'' passing through the point *b*, since the input admittance to be presented by the attenuator to the transmission line section 12'' extending to the source 5'' is not to be made equal to that represented by the vector *ab*. The admittance of the dissipator 9'' and the equal admittance of the dissipator 9''', may be smaller or larger than shown in Fig. 5, if desired. The primary requirement of the dielectric body 8'' in this attenuator system is that it compensate for the susceptances of dissipators 9'' and 9''', and this is readily accomplished for whatever reciprocal abscissae circle on which the vector *bc* or *bc'* corresponding to dissipator 9'' may terminate.

Thus, if dissipators 9'' and 9''' have somewhat less admittance than shown in Fig. 5 by the equal vectors *bc*, *de*, and *d'b'*, then such dissipators may be represented by the vectors *bc'*, *d''e'*, and *d'''b''*. The effective electrical length of a body 8'' made of polystyrene for use with these lower-admittance attenuators may then be 2×15° or 30° for an input admittance *ae'*. Similarly, the effective electrical length of body 8'' may be 15°+58°, or 73° for an input admittance *ab''*. The circle 14''' passing through points *c'*, *d''* and *d'''* represents the transformation through the dielectric body 8'' effected for dissipators of the admittance represented by vector *bc'*. The points *d''* and *d'''* are located on circle 14''' as the points having ordinates of equal magnitude but opposite sign to the point *c'* at which vector *bc'* terminates. A similar analysis may be carried out for dissipators of greater admittance than represented by vector *bc*.

The section 12'' of the transmission line 3'', 4'' extending from the input end of the attenuator section 11'' to the source 5'' is shown as having an appreciably greater inner conductor diameter than the other portions of the transmission line. Such a section 12'' thus would have much greater characteristic admittance than the characteristic admittance of section 13'' and the conductance of load 6''. Accordingly, the much increased input admittance presented by attenuator section 11'' to the transmission line section 12'' may match the characteristic impedance of the latter, so that a completely matched transmission system is provided. The characteristic admittance of section 12'' of the transmission line also may be increased by the use of an outer conductor having reduced diameter, or by use of a dielectric filling of dielectric constant appreciably greater than unity.

In the system of Fig. 4, a construction of the concentric line 3'', 4'' is shown whereby attenuator sections may be removed or added as desired. For this purpose, a plug-in transmission line junction is provided in section 12'' of the transmission line 3'', 4'', and a second, similar junction is provided within section 13'' of the line. To form such a plug-in junction, the outer conductor 4'' ends in a plane perpendicular to the axis of the transmission line, and the inner conductor 3'' ends at two points substantially ⅛λ from the planes defined by the ends of the outer conductor 4''. Two thin dielectric discs 17 and 17' are fitted into outer conductor 4'' and are provided with centrally located holes for supporting the ends thus formed of inner conductor 3''. Thus, when two transmission line ends are connected together, the thin dielectric discs are separated by substantially λ/4, so that the reflections from the two discs are cancelled.

The ends of inner conductor 3'' are drilled centrally to provide sockets for connecting to and supporting an inner conductor junction member 19. The latter member comprises a main body of diameter equal to the diameter of the inner conductor ends joined thereby, with the ends of the junction member 19 turned down to fit snugly into the drilled ends of the inner conductor portions. An outer sleeve 21 is provided to fit snugly over the abutting ends of outer conductor 4'', to complete the junction.

By the construction of transmission line attenuator sections having such ends adapted for plug-in connections the removal, addition, or interchange of attenuator units may be greatly facilitated.

As explained in detail above, the asymmetrical attenuator section of Fig. 1 provides a matched impedance condition for transmission in one direction only, while that of Fig. 4, although symmetrical, fails to provide an input impedance equal to its output impedance. A transmission line attenuator section shown in Fig. 6 embodies a symmetrical combination of parts, and at the same time provides an input admittance equal to the terminating admittance.

A portion of a coaxial transmission line having a uniform diameter inner conductor 23 and a uniform diameter outer conductor 24 is shown in Fig. 6. Three successive dissipator elements 25, 26 and 27 are positioned at intervals along a portion of transmission line 23, 24, separated and mechanically supported by solid dielectric bodies 28 and 29.

The admittance diagram of Fig. 7 illustrates the manner in which the dielectric bodies 28 and 29 cooperate with the dissipators 25, 26 and 27 to produce the desirable attenuator characteristics of symmetry and over-all impedance match discussed above. The vector *ab*, as in the preceding admittance diagrams, represents the characteristic admittance of air-filled portions of the coaxial line 23, 24. A relatively low admittance element 27 acts in shunt with the transmission line 23, 24 which is assumed to be terminated in its characteristic admittance.

The inclination of the vector *bc* corresponds to the phase angle above discussed for certain measured samples of dissipator elements for frequencies of the order of 3000 megacycles. The sum of the admittances *ab* and *bc*, represented by the location of the point *c* in Fig. 7, corresponds to a slightly capacitive admittance somewhat smaller than the characteristic admittance of the portions of transmission line 23, 24 filled by bodies 28 and 29 of a solid dielectric material such as polystyrene, for example. The solid dielectric body 29 may be made in a length corresponding to approximately 90° effective electrical length, and thus the admittance transformation through the section of transmission line 23, 24 filled by the solid dielectric body 29 may be represented by the arc *cd*. The physical length of the body 29 may be computed as

$$\frac{90^\circ}{360^\circ}\cdot\frac{\lambda}{\sqrt{\epsilon}}$$

or approximately 1.6 centimeters for a frequency of 3000 megacycles and polystyrene dielectric material.

The middle dissipator 26 of the attenuator shown in Fig. 6 preferably is quite large compared to the end dissipators 25 and 27. The admittance of this dissipator is represented in Fig. 7 by the vector *de*, as acting in shunt with the transmission line 23, 24 at the sending end of the solid dielectric body 29. It is noted that an arc *ef* of substantially 90° extent, representing the further impedance transformation provided by the section of transmission line 23, 24 filled by solid dielectric body 28, provides an admittance (represented by the point *f*) which is slightly inductive and which is somewhat smaller than the termination admittance *ab*. The admittance of the input end dissipator 25, equal to the admittance of the termination end dissipator 27, is then represented by the vector *fb*, which shows clearly that the input impedance of the properly terminated attenuator section of the coaxial line 23, 24 is equal to the terminating impedance thereof, which, of course, is equal to the characteristic admittance of the air-filled portions of transmission line 23, 24.

Actually, to expedite an acceptable solution for the dimensions and dissipator admittance values of Fig. 6, the size of the end dissipators 25 and 27 may be arbitrarily chosen and both vectors *bc* and *fb* may be located on the admittance diagram. The circles 31 and 32 passing through points *f* and *c*, respectively, then may be located, and finally, a straight edge may be moved parallel to the vectors *fb* and *bc* until arcs *cd* and *ef*, as measured by the effective electrical phase angle calibrations thereof, are found to be equal. This locates the vector *de*, and enables one to complete the circle diagram and to graphically determine the admittance value which should characterize the middle dissipator 26.

The solid dielectric bodies 28 and 29, being of approximately 90° electrical length as shown by the circle diagram of Fig. 7, should be cut to lengths determined by

$$\frac{90}{360}\cdot\frac{\lambda}{\sqrt{\epsilon}}$$

or approximately 1.6 centimeters each.

As also pointed out in connection with the attenuator device of Fig. 1, a plurality of systems such as that shown in Fig. 6 may be employed in cascade for very large attenuation ratios. Ordinarily, however, the flexibility of design of the attenuator embodiment shown in Fig. 6 permits of providing any desired attenuation value within a wide range without even the requirement of any change of dielectric material of bodies 28 and 29.

A further symmetrical attenuator embodiment which presents an input admittance equal to the load or termination admittance is shown in Fig. 8. This attenuator arrangement is closely related to that of Fig. 6, being comparable in size to the above attenuator. However, the dissipation in the attenuator of Fig. 8 is continuously distributed throughout the length of the dielectric body. For this purpose, the dielectric body 35 which is positioned intermediate the inner conductor 33 and the outer conductor 34 of coaxial transmission line 33, 34 is purposely made of a material characterized by very high energy loss at the frequency of the energy to be transmitted. The material 35 may be made up by incorporating carbon particles or other high-loss material within a plastic base. Alternatively, a material which is ordinarily considered a good insulator at low frequencies but which is relatively inefficient at the high frequencies may be employed for the construction of dielectric body 35. The length of the body 35 preferably should be such as to have an effective electrical length of 180° or an integral multiple of 180°, since such a length results in a complete cycle of impedance change, and the input impedance is therefore equal to the termination impedance. Thus, the physical length of the body 35 should be made approximately equal to

$$\frac{n\lambda}{2\sqrt{\epsilon}}$$

where ϵ is the real component of the dielectric constant of the high-loss material 35, and n is an integer.

In all of the foregoing attenuator embodiments of the present invention, the transmission line conductors have been shown as being of uniform diameter throughout the solid dielectric bodies and also throughout the air-filled transmission line portions 13 and 13'' extending to the load. Actually, such an arrangement is entirely satisfactory if the material chosen for the solid dielectric bodies 8, 8'', 28, 29 and 35 is of a dielectric constant and other characteristics permitting a desired resultant attenuation characteristic in the device.

In the attenuator of Fig. 1, for example, as explained in connection with the admittance diagram of Fig. 3, the location of the point b on the admittance diagram is determined as the point whose abscissa is given by

$$\frac{Y_0'}{Y_0}=\frac{1}{\sqrt{\epsilon}}$$

Since solid dielectric material suitable for use in high frequency transmission devices is not available in a wide and continuous range of dielectric constants, it may be desirable so to change the diameter of either or both of the conductors 3 and 4 throughout the axial extent of the dielectric body 8 as to produce through the section 11 of the transmission line a characteristic admittance value Y_0 either lower than or greater than the characteristic admittance which would be produced with uniform diameter conductors, but yet different from the characteristic admittance Y_0' of the air-filled sections 12 and 13 of the transmission line 3, 4.

Fig. 9 shows an attenuator generally similar to that of Fig. 1, but different in the respect that the inner conductor 43 of the attenuator of Fig. 9 is enlarged to a greater diameter over a portion 43' extending throughout the axial length of the solid dielectric body 48, which, as before, is fitted snugly into the uniform diameter outer conductor 44. The solid dielectric body 48 in the attenuator of Fig. 9 serves to increase the characteristic admittance of the transmission line section filled thereby, just as does the solid dielectric body 8 of the attenuator of Fig. 1. The enlarged diameter of inner conductor 43 throughout the section 43' further acts to increase the characteristic admittance of the transmission line section including the solid dielectric body 48.

By the combined effects of the increased dielectric constant and the reduced diametral ratio of the uniform diameter outer conductor and the enlarged inner conductor, the section of the transmission line 43, 44 which is filled with the solid dielectric body 48 is characterized by a much higher characteristic admittance than the section 11 of the attenuator shown in Fig. 1. It will readily be seen from a study of the admittance diagram of Fig. 3 that such a further increase of characteristic admittance of the solid dielectric-filled transmission line section would result in a trace of an arc similar to cb along a much greater diameter circle than the circle 14. This would be accompanied by a relatively smaller vector ab and a much larger dissipator admittance bc, and accordingly, a much higher relative attenuation would be provided in the structure of Fig. 9. Thus, even if only one kind of dielectric material is available or suitable for the construction of an attenuator of the general class shown in Figs. 1 and 9, variation of the conductor diameters may be employed to provide an attenuator of any desired characteristics within an exceedingly wide range.

A change of conductor diameter may be made in a symmetrical attenuator of the general type shown in Fig. 6. By such a change of conductor diameter, which may be accomplished either as shown in Fig. 10 through a reduction in size of the inner conductor, for example, or as shown in Fig. 11 through the use of an outer conductor of increased diameter, the characteristic admittance Y_0 of solid dielectric-filled portions of the transmission line may be made substantially equal to the characteristic admittance Y_0' of the air-filled transmission line portions external of the attenuator unit.

The embodiments of present invention shown in Figs. 10 and 11 thus may be made to operate electrically just as though very thin discs or wafers of dissipating material 25', 26' and 27' (or 25'', 26'' and 27'') were inserted within a coaxial transmission line and spaced therein in a self-supporting manner, without the dielectric bodies 28', 29' (or 28'', 29''). In such an attenuator structure as that shown in Fig. 10, the admittance of the middle dissipator should then be substantially double that of each of the end dissipators 25' and 27'. Similarly, the admittance of the middle dissipator 26'' in the attenuator of Fig. 11 should be substantially double the admittance of the end dissipators 25'' and 27''.

Thus, in the attenuator arrangements of Figs. 10 and 11, an attenuating system is provided which electrically is nearly equivalent to that shown in Fig. 4 of U. S. patent application Serial No. 452,319, filed July 25, 1942, now Patent No. 2,514,544, issued July 11, 1950 in the name of William W. Hansen. Mechanically, however, the attenuator arrangements of Figs. 10 and 11 are greatly enhanced by the rigid support for the dissipators 25′, 26′, 27′ and 25″, 26″, 27″ afforded by the axially extensive solid dielectric bodies which fill the intervening space between successive dissipator elements. As in the Hansen application, the response for varying frequency may be still more improved by adding more dissipators, spaced by the same distances as the three elements of Fig. 10 and having admittances substantially proportional to the binomial coefficients of the expansion of a binomial of order of one less than the total number of dissipator elements.

The attenuator versions of Figs. 9, 10, and 11 all are characterized by a change of diameter of either the inner conductor or the outer conductor throughout the axial extent of solid dielectric bodies inserted into the line and made a part of the respective attenuators. If desired, the diameter of the inner conductor of a coaxial transmission line may be reduced throughout the length of a solid dielectric body, and the cooperating outer conductor diameter may be increased over the same portion of the transmission line. Such a modification of the structure of Fig. 8 is shown in Fig. 12. Thus, a large increase in the ratio of the diameters of the outer conductor and the inner conductor conveniently may be provided without an extremely large change of diameter of either conductor.

If the ratio of the logarithm of the diametral ratio throughout the extent of the solid dielectric body 35′ to the logarithm of the diametral ratio of conductors 34′ and 33′ extending beyond the solid dielectric body 35′ is equal to $\sqrt{\epsilon}$, then the characteristic impedance of the transmission line portion filled by the solid dielectric body 35′ will be equal to the characteristic impedance of the air-filled portion of transmission line 33′, 34′. In this event, the structure of Fig. 12, while able to function generally like the distributed-loss attenuator of Fig. 8, may be made of substantially any length desired without the introduction of an impedance mismatch between the termination or load and the input impedance.

Substantially all of the attenuator structures shown in Figs. 1, 4, 6 and 8 through 12 are suitable for incorporation within a hollow-pipe wave guide, if desired.

For example, Fig. 13 shows a hollow-pipe wave guide 41 in which is inserted a solid dielectric body 58 and a dissipative element 59, substantially similar to the corresponding elements of Fig. 1 except that no passage is provided through the solid dielectric body 58 and the dissipator 59 for a central conductor. As in the previous examples, the solid dielectric body 58 serves both as a mechanical support for the dissipator element 59 and also as an impedance transformer within the wave guide section occupied thereby. A similar adaptation to use within a hollow-pipe wave guide may be made of any of the other embodiments of the present invention which have been illustrated especially as applied to coaxial transmission lines.

To summarize briefly the important aspects of the present invention, an axially extensive solid dielectric body is employed in a hollow high-frequency conductor as a rigid support of high mechanical strength for a dissipator element or elements, or for distributed dissipative material. The solid dielectric body and the dissipative material cooperate with the high frequency conductor to form an attenuator section therein. At the same time, the solid dielectric body may introduce a discontinuity of characteristic admittance within the high frequency conductor section occupied thereby, which thus may serve as an admittance transformer for producing a desired input admittance as measured at the input end of the attenuator when the output end thereof is properly terminated in a suitable load. Furthermore, if dissipator elements having appreciable susceptance as well as conductive admittance are employed, the solid dielectric bodies referred to above may be made of such characteristics and dimensions as to compensate fully for the susceptance introduced by the dissipative elements, so that a conductive input admittance may be provided as desired at the high frequency input end of the attenuator.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. Attenuator apparatus for conducting high frequency energy from a first section of coaxial line to a second section thereof comprising a relatively thin dissipator element extending across the space within said coaxial line adjacent said second section and having appreciable admittance effectively in shunt with the admittance of said second section, and means for transforming the resultant effective shunt admittance of said second section and said dissipator element into a desired input admittance comprising a dielectric body within said hollow conductor adjoining said dissipator element to provide support therefor and extending along said coaxial line toward said first section thereof through a length appreciable compared to the quotient of one-fourth the wavelength of said high frequency energy divided by the square root of the dielectric constant of said dielectric body, the diameter of one of the coaxial electric current conductors comprising said coaxial transmission line through the length of said dielectric body being different from the diameter of said conductor in said second section.

2. Symmetrical attenuator apparatus for dissipating a predetermined fraction of high frequency energy conducted from a first section of a hollow high frequency energy conductor toward a second section of said conductor and for presenting to said first conductor section an admittance substantially equal to the admittance of said second section, comprising a first relatively thin dissipator element extending across the space within said hollow energy conductor adjacent said first section thereof, a second relatively thin dissipator element extending across the space within said hollow energy conductor adjacent said second section thereof, said first and second dissipator elements having equal admittances appreciable in relation to the characteristic admittance of said hollow high frequency energy conductor, a third relatively thin dissipator element extending across the space within said hollow energy conductor and positioned midway between said first and second dissipator elements, said third dissipator element having an admittance substantially twice the admittance value characterizing each of said first and second dissipator elements, a first dielectric body

filling the space within said hollow high frequency conductor between said first dissipator element and said third dissipator element, a second dielectric body filling the space within said hollow high frequency energy conductor between said third dissipator element and said second dissipator element, said first dielectric body providing mechanical support for said first dissipator element, said second dielectric body providing mechanical support for said second dissipator element, and said first and second dielectric bodies jointly providing mechanical support for said third dissipator element positioned therebetween, said first dielectric body and said second dielectric body being of appreciable length compared to the quotient of one-fourth of the wavelength of said high frequency energy divided by the dielectric constant of said first and second dielectric bodies.

3. Symmetrical attenuator apparatus as set forth in claim 2, wherein said hollow high frequency energy conductor comprises the outer conductor of a coaxial transmission line.

4. Symmetrical attenuator apparatus for dissipating a predetermined fraction of high frequency energy conducted from a first section of coaxial line toward a second section of said coaxial line for presenting to said first coaxial line section an admittance substantially equal to the admittance of said second section comprising a first relatively thin dissipator element extending across the space within said coaxial line adjacent said first section thereof; a second relatively thin dissipator element extending across the space within said coaxial line adjacent said second section thereof; a third relatively thin dissipator element extending across the space within said coaxial line and positioned midway between said first and second dissipator elements, said first, second and third dissipator elements having appreciable admittance in shunt with the admittance of said coaxial line; a first dielectric body within said coaxial line extending from said first dissipator element to said third dissipator element; and a second dielectric body within said coaxial line extending from said third dissipator element to said second dissipator element, said first dielectric body providing mechanical support for said first dissipator element, said second dielectric body providing mechanical support for said second dissipator element, said first and second dielectric bodies jointly providing mechanical support for said third dissipator element

positioned therebetween, each of said dielectric bodies being of a length of the order of

$$\frac{\lambda}{4\sqrt{\epsilon}}$$

where λ is the wavelength and ϵ is the dielectric constant of said dielectric bodies, and the diameter of one electric current conductor of said coaxial transmission line throughout the extent of said first and second dielectric bodies being different from the diameter of said conductor in said second section of said transmission line.

5. An attenuator for high frequency energy comprising a first section of transmission line; a second section of transmission line; and a third section of transmission line interconnecting said first and second sections of transmission line and including more than two dissipator members across said transmission line whose admittances correspond to the binomial coefficients of order one less than the number of said dissipator members, said third section also including solid dielectric bodies completely filling the spaces between successive dissipator elements, whereby said dielectric bodies support said dissipator elements.

6. Apparatus as in claim 5 in which the plurality of dissipator elements are equally spaced.

7. Apparatus as in claim 5 in which said third section of transmission line has a characteristic impedance substantially equal to the characteristic impedance of said first section of coaxial line.

EUGENE FEENBERG.

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Certificate of Correction

Patent No. 2,538,771

January 23, 1951

EUGENE FEENBERG

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows:

Column 5, line 74, for "γ" read λ; column 7, line 32, before the word "or" insert an opening parenthesis; column 9, line 16, after "this" insert *is*;

and that the said Letters Patent should be read as corrected above, so that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 10th day of July, A. D. 1951.

[SEAL]

ERNEST F. KLINGE,
Assistant Commissioner of Patents.