

April 2, 1957

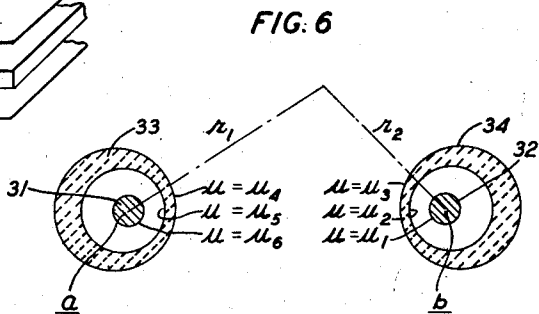
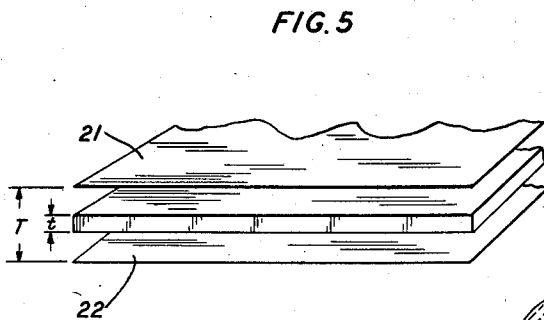
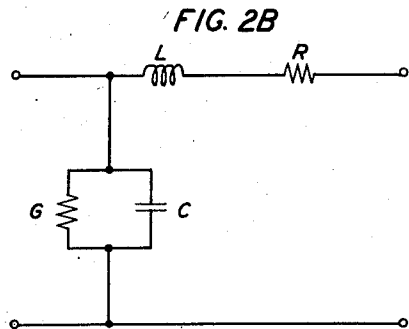
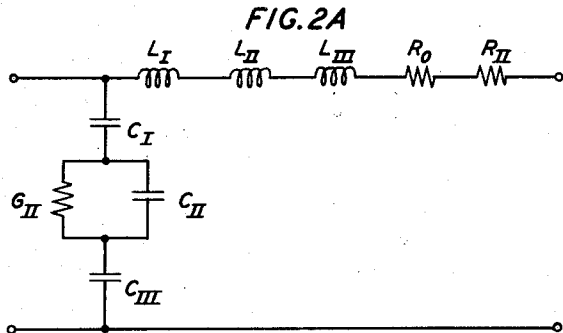
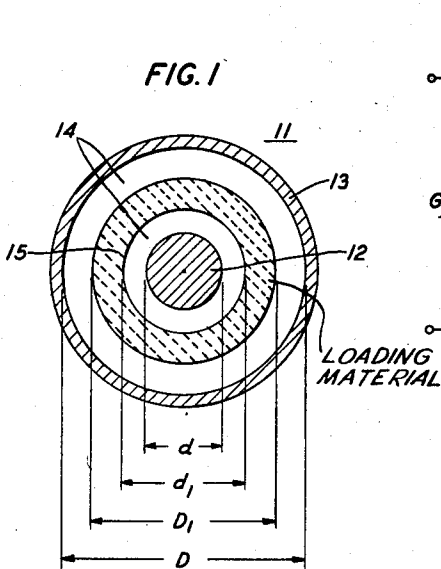
G. RAISBECK

2,787,656

MAGNETICALLY LOADED CONDUCTORS

Filed Dec. 30, 1954

2 Sheets-Sheet 1



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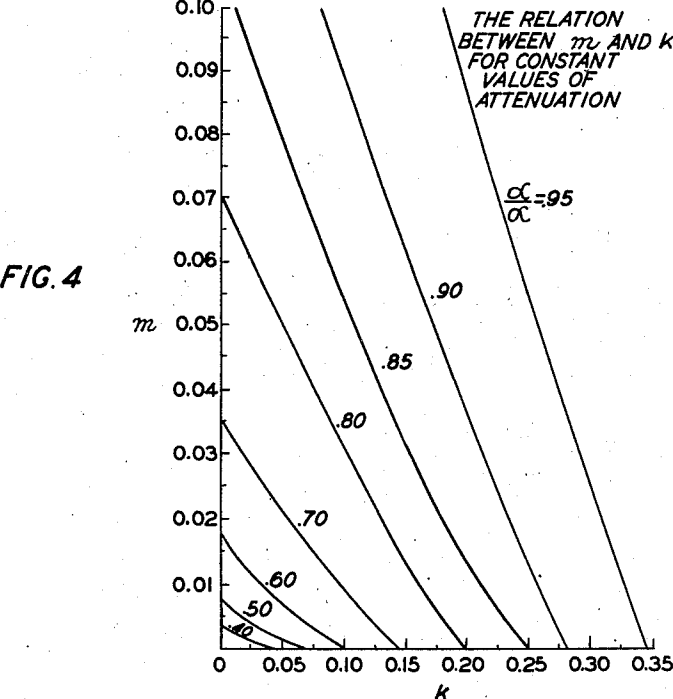
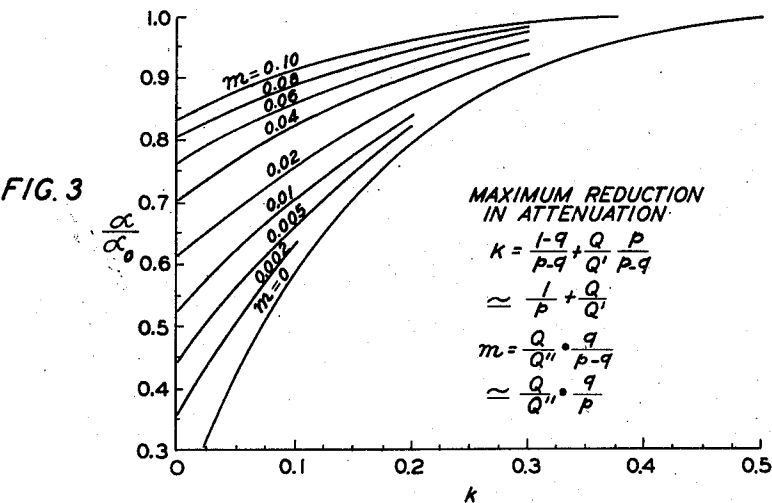
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MAGNETICALLY LOADED CONDUCTORS

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Application December 30, 1954, Serial No. 478,680

2 Claims. (Cl. 178-45)

This invention relates to transmission lines for use in the propagation of electromagnetic waves.

More particularly, this invention relates to magnetically loaded transmission lines having a low attenuation per unit length as compared to similar, unloaded transmission lines.

It is an object of this invention to provide a magnetically loaded transmission line having a low attenuation per unit length.

More particularly, it is an object of this invention to provide a transmission line in which the optimum magnetic loading effects are realized for a line of given geometrical configuration.

The benefits to be gained from magnetically loading a transmission line have long been appreciated. In a properly loaded line, the magnetic permeability of the loading material increases the inductance per unit length of the line, resulting in an increase in the intrinsic impedance thereof and a consequent decrease in attenuation per unit length. Heretofore, efforts to reduce the attenuation of a line by magnetic loading have been only partially successful, since the magnetic material, if conductive, introduces extra losses into the line, or if non-conductive, increases the capacitance of the line.

Several schemes for continuously loading a line have been proposed, but it has been found that where the loading material is continuous, the hysteresis and eddy current losses more than nullify the beneficial results of the loading. In an effort to eliminate these undesirable effects, suspensions of powdered magnetic material in dielectric material have been proposed, but the resulting permeability of the mass has been too low to be of any appreciable benefit.

Materials such as ferrites, which have a high magnetic permeability and a high resistance, appear to be the most promising materials for magnetic loading. However, such materials, when used in a continuous loading arrangement, exhibit such high hysteresis losses that there is no benefit to be gained. The hysteresis losses can be minimized by introducing air gaps into the geometry of the loading material, but the presence of air gaps results in an unequal current distribution in the conductors. This effect can be at least partially overcome by imparting to the conductors irregular shapes or configurations, which are reached through trial and error experimentations.

In a paper entitled "Noyaux et Coquilles dans la Domaine des Telecommunications," in Cables et Transmission, vol. 6, 1 and 2, 1952, by M. Prache, a thorough study is presented of the loading problem in the specialized case of a coaxial line with a concentric shell of loading material between the inner and outer conductor. While the problem is treated with great detail, and optimized specifications for the numerous parameters are obtained, the solution fails to take into account the dielectric loss tangent, it being assumed throughout that this parameter is zero, with a result that optimum loading is not attained.

The present invention is based upon a mathematical treatment which, after a change of variables, yields only

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three parameters, including dielectric losses, making possible an optimum proportioning of the transmission line variables regardless of the geometry of the line. In a preferred embodiment, the invention comprises a coaxial transmission line having a concentric shell of magnetic loading material such as ferrite disposed between the inner and outer conductors. The dimensions of the inner and outer conductors and of the shell of loading material are so proportioned relative to each other and to the other parameters of the line that the attenuation per unit length of the line is considerably less than heretofore obtainable through magnetic loading.

Various other illustrative embodiments will be described herein, each of which is characterized by continuous magnetic loading and an optimum proportioning of the parameters, resulting in a considerable decrease in attenuation.

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

Fig. 1 is a cross-section view of a coaxial cable embodying the principles of the invention;

Fig. 2A is an equivalent circuit of the cable of Fig. 1;

Fig. 2B is a simplified equivalent circuit of the cable of Fig. 1;

Figs. 3 and 4 are graphs of the performance characteristics of transmission lines embodying the invention;

Fig. 5 is a perspective view of a preferred embodiment of the invention; and

Fig. 6 is a cross-sectional view of still another preferred embodiment.

Turning now to Fig. 1, there is shown a coaxial cable 11 comprising an inner conductor 12 having an outer diameter d , an outer conductor 13 having an inner diameter D , and a dielectric or insulator 14 separating the two conductors. A hollow cylindrical member 15 having an inner diameter d_1 and an outer diameter D_1 and made of magnetic material which, for reasons stated in the foregoing, is preferably a high permeability, high resistance material such as ferrite, is interposed between the inner and outer conductors concentrically therewith. Dielectric 14 has a permeability μ_0 and a dielectric constant ϵ_0 , while the loading member 15 has a tangential permeability μ and a radial dielectric constant ϵ . The imaginary components of μ and ϵ are taken into account in the form of figures of merit Q' and Q'' , which will be explained more fully hereinafter.

An equivalent circuit of a unit length of line is shown in Fig. 2A, wherein L_1 is the inductance due to fields between d and d_1 , L_{11} is the inductance between d_1 and D_1 , and L_{12} is the inductance between D_1 and D . R_0 is the series conductor resistance and R_{11} is the loss associated with L_{11} . In like manner C_1 is the capacitance between d and d_1 , C_{11} the capacitance between d_1 and D_1 , and C_{12} the capacitance between D_1 and D . In addition, G_{11} is the loss conductance associated with C_{11} . For purposes of the present analysis, it is permissible to assume that the dielectric 14 is free of loss and that the frequency is high enough so that all current flow is at the surface of the conductors.

The inductance of a coaxial line is given by the expression

$$L = \frac{\mu}{2\pi\epsilon} \log \frac{D}{d} \quad (1)$$

and the capacitance by

$$\frac{1}{C} = \frac{1}{2\pi\epsilon} \log \frac{D}{d} \quad (2)$$

where D is the inner diameter of the outer conductor

and d is the outer diameter of the inner conductor. In addition, for a coaxial line

$$R = \frac{2\pi fL}{Q} \quad (3)$$

where f is the frequency and Q is described as the ratio of the peak energy stored to the energy lost per radian. Thus R_{II} becomes

$$R_{II} = \frac{2\pi fL_{II}}{Q'} \quad (4)$$

where Q' is the reciprocal of the magnetic loss tangent of the loading material. The loss conductance is given by

$$G_{II} = \frac{2\pi fC_{II}}{Q''} \quad (5)$$

where Q'' is the reciprocal of the dielectric loss tangent of the loading material.

It is a simple matter to combine the various elements of Fig. 2A into the equivalent circuit of Fig. 2B. It can readily be shown that in such case

$$L = \frac{\mu_0}{2\pi} \left[\log \frac{Dd_1}{D_1d} + \frac{\mu}{\mu_0} \log \frac{D_1}{d_1} \right] \quad (6)$$

$$R = f\mu_0 \left[\frac{1}{Q} \log \frac{D}{d} + \frac{\mu/\mu_0}{Q'} \log \frac{D_1}{d_1} \right] \quad (7)$$

$$\frac{1}{C} = \frac{1}{2\pi\epsilon_0} \left[\log \frac{Dd_1}{D_1d} + \frac{\epsilon_0}{\epsilon} \log \frac{D_1}{d_1} \right] \quad (8)$$

$$G = \frac{2\pi}{Q''} \left[\frac{2\pi\epsilon_0\epsilon_0}{\epsilon} \log \frac{D_1}{d_1} + \log \frac{Dd_1}{D_1d} + \frac{\epsilon_0}{\epsilon} \log \frac{D_1}{d_1} \right]^2 \quad (9)$$

From the expression for attenuation in a coaxial line

$$\alpha = \frac{R}{2\sqrt{L}} + \frac{G}{2\sqrt{C}} \quad (10)$$

it can be shown that, in the case of an unloaded line

$$\left(Q' = Q'' = \infty, \frac{\mu}{\mu_0} = \frac{\epsilon_0}{\epsilon} = 1 \right) \quad (11)$$

$$\alpha_0 = \frac{\pi f \sqrt{\mu_0 \epsilon_0}}{Q} \quad (12)$$

By letting

$$X = \frac{\log \frac{D}{d}}{\log \frac{D_1}{d_1}} \quad (13)$$

and combining Equations 6 through 12, we arrive at the expression

$$\frac{\alpha}{\alpha_0} = \frac{X + \frac{Q\mu}{Q'\mu_0}}{\sqrt{\left(X + \frac{\mu}{\mu_0} - 1\right)\left(X + \frac{\epsilon_0}{\epsilon} - 1\right)}} + \frac{\frac{\epsilon_0 Q}{\epsilon Q''} \sqrt{\left(X + \frac{\mu}{\mu_0} - 1\right)\left(X + \frac{\epsilon_0}{\epsilon} - 1\right)}}{\left(X + \frac{\epsilon_0}{\epsilon} - 1\right)^2} \quad (14)$$

For simplicity, let

$$k = \frac{1 - \frac{\epsilon_0}{\epsilon}}{\frac{\mu}{\mu_0} - \frac{\epsilon_0}{\epsilon}} + \frac{Q}{Q'} \frac{\frac{\mu}{\mu_0}}{\frac{\mu}{\mu_0} - \frac{\epsilon_0}{\epsilon}} = \frac{1 - q}{p - q} + \frac{Q}{Q'} \frac{p}{p - q} \quad (15)$$

$$m = \frac{Q}{Q''} \frac{\frac{\epsilon_0}{\epsilon}}{\frac{\mu}{\mu_0} - \frac{\epsilon_0}{\epsilon}} = \frac{Q}{Q''} \frac{q}{p - q} \quad (16)$$

$$v = \frac{X + \frac{\epsilon_0}{\epsilon} - 1}{\frac{\mu}{\mu_0} - \frac{\epsilon_0}{\epsilon}} = \frac{X + q - 1}{p - q} \quad (17)$$

10 then

$$\frac{\alpha}{\alpha_0} = \frac{k}{\sqrt{v(v+1)}} + \frac{\sqrt{v}}{\sqrt{v+1}} + \frac{m\sqrt{v+1}}{v\sqrt{v}} \quad (18)$$

15 Regarding Q, Q', Q'' ,

$$p \left(p = \frac{\mu}{\mu_0} \right), q \left(q = \frac{\epsilon_0}{\epsilon} \right),$$

20 d, d_1 , and D_1 as independent parameters, it is apparent that all of the variables in Equations 14 through 17 are independent of the dimensions of the line except v . The optimum dimensions of the line may, therefore, be readily obtained by differentiating Equation 17 with respect to v and setting the derivative equal to zero, from which we get

$$v = \frac{k + 5m + \sqrt{k^2 - 14mk + m^2 + 12m}}{2(1 - 2k - 2m)} \quad (19)$$

at which point

$$\frac{\alpha}{\alpha_0} = \sqrt{\frac{8(1-k)(2k-2m+\sqrt{k^2-14mk+m^2+12m})}{9(k-m)+\sqrt{k^2-14mk+m^2+12m}}} \quad (20)$$

Figures 3 and 4 are graphs of Equation 19 for differing values of m and k . Inspection of the curves of Fig. 3 reveals the effect of dielectric loss, which is included in the parameter m . The family of curves represents fixed values of m and the consequent variation in loss

$$\left(\frac{\alpha}{\alpha_0} \right)$$

for varying k . It can be seen from Fig. 4 that

$$\frac{\alpha}{\alpha_0}$$

decreases, the slope of the curve decreases, and the role of m , and consequently, dielectric loss, becomes more important compared to k . The utility of the curves of Figs. 3 and 4 is obvious. They show to what extent one kind of loss may be substituted for another. In addition, for a given line size, it is possible to compute the values of k and m for available magnetic materials, and then determine from Figs. 3 and 4 whether it is feasible to construct such magnetically loaded line.

Having arrived at an expression for minimum attenuation, it becomes a simple matter to determine the dimensions of the line which, for a given group of materials, yields the minimum attenuation possible. Rearranging Equation 16, an expression is obtained for the ratio D_1/d_1 which gives the optimum dimensions for minimum attenuation, thus

$$\log \frac{D_1}{d_1} = \frac{\log \frac{D}{d}}{v(p-q)-q+1} \quad (21)$$

It can be seen from Equation 20 that the magnitudes of the dimensions D, d, D_1 and d_1 do not matter so long as the ratio D_1/d_1 and D/d satisfy the equation. It follows from this, then, that the value of the ratio D/d which minimizes α_0 , which, as is well known, is equal to 3.59, should be used to minimize α also. This fact can be readily verified by inspection of Equation 17.

As an illustration of the difference in results reached

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when dielectric losses are considered, assume that available materials have the following set of parameter values:

$$Q=17.8$$

$$\frac{\mu}{\mu_0}=9.8, \frac{E_0}{E}=0.44$$

$Q'=320$, and $Q''=40$. In the aforementioned Prache article, the method there presented assumes $Q''=\alpha$ and $k=0$, and the result reached is

$$\frac{D_1}{d_1}=1.89$$

This gives an expected

$$\frac{\alpha}{\alpha_0}$$

of 0.65. However, because of dielectric loss, the actual value of

$$\frac{\alpha}{\alpha_0}$$

is 1.02. The method herein proposed leads to the following results

$$\frac{D_1}{d_1}=1.277$$

and

$$\frac{\alpha}{\alpha_1}=0.779$$

It is obvious that failure to consider dielectric losses leads to a result which is not the optimum obtainable, whereas the present method produces optimum dimensioning of the cable and loading material for a given group of materials.

The present invention has been set forth in the foregoing in the preferred embodiment of a coaxial cable. Actually, however, the principles of the invention are equally applicable to other types of conductors also, provided that the boundaries of the loading material are surfaces which would be equipotentials if the loading material were removed. When this condition is met, Equations 6 through 9 become, respectively:

$$L=L_0\left(1+\frac{p-1}{X}\right) \quad (21)$$

$$R=R_0\left(1+\frac{pQ}{Q'}-\frac{1}{X}\right) \quad (22)$$

$$\frac{1}{C}=\frac{1}{C}\left(1+\frac{q-1}{X}\right) \quad (23)$$

$$G=\frac{C_0}{Q''}\frac{Xq}{(X+q-1)^2} \quad (24)$$

where X is a number independent of anything except the geometrical configuration of the loaded line, and for the sake of simplicity shall be referred to as the geometric configuration parameter.

In Fig. 5 there is shown a pair of flat conductors 21 and 22 of infinite extent separated by a distance T . Positioned between the conductors is a member 23 of loading material such as ferrite, having a thickness t . Inasmuch as the dimensions of length and breadth do not enter into the computations in this case, the parameter X becomes

$$X=\frac{T}{t} \quad (25)$$

and Equations 13 and 17 through 19 apply without modification.

In Fig. 6 there is shown a pair of parallel conductors 31 and 32, with magnetic loading members 33 and 34, which are of ferrite or other suitable loading material.

As is well known, when two current carrying conductors are in close proximity to each other, the magnetic field around each conductor will influence the current in the other conductor, resulting in an uneven current dis-

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tribution. This phenomenon is known as "proximity effect." If such a pair of conductors is to be magnetically loaded as shown in Fig. 6, the influence of the magnetic field surrounding each wire must be considered, inasmuch as that portion of loading member 33 nearest conductor 32 is under the influence of stronger magnetic fields than that portion remote from conductor 32 and vice versa. The same conditions apply to member 34 and its relationship to conductor 31. By use of a system of bi-polar coordinates, it becomes a relatively simple matter to take into account the proximity effect in designing and dimensioning the loading members. An explanation of bi-polar coordinates and their relationship to magnetic fields can be found in "Electromagnetic Theory" by J. A. Shatton (McGraw-Hill, 1941). Such a system requires the selection of two points a and b with respect to which any circle must satisfy the relationship:

$$\frac{r_a}{r_b}=\text{constant}=\mu \quad (26)$$

where r_a is the distance from point a to any point on the circle and r_b is the distance from point b to any point on the circle. It can be seen that for different values of μ , a family of circles is described, the centers of which lie on a line joining points a and b and which are asymmetrically disposed with respect to the points a and b . In Fig. 6, this constant is designated μ_1 for the surface of conductor 32, μ_2 for the inner surface of loading member 34, and μ_3 for the outer surface of loading member 34. In like manner μ_4 designates the outer surface of member 33, μ_5 the inner surface, and μ_6 the surface of conductor 31. The net result is that the various members are asymmetrical with respect to the point a and b , and are not concentric with each other. In such a case, the geometric configuration parameter becomes:

$$X=\frac{\log \mu_1/\mu_4}{\log \mu_2/\mu_3+\log \mu_4/\mu_5} \quad (27)$$

For a symmetrical system, $\mu_1=1/\mu_6$, $\mu_2=1/\mu_5$, and $\mu_3=1/\mu_4$ and

$$X=\frac{\log \mu_1}{\log \mu_2/\mu_3} \quad (28)$$

In the foregoing discussion of the various embodiments, it was assumed that the space separating the loading members from the conductors is filled with the same dielectric as the space surrounding the arrangement. If such is not the case, another variable is introduced into the problem. This, however, does not affect the basic concepts constituting the principles of the invention, although it results in a somewhat more tedious mathematical reduction to the basic formula.

While the principles of the invention have been set forth in detail as applied to certain specific embodiments, it is to be understood that these embodiments are by way of illustration. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention as set forth in the appended claims.

What is claimed is:

1. A transmission line of the coaxial conductor type having conducting and dielectric portions, magnetic loading material of cylindrical shape interposed between and spaced from the inner and outer conductors, said loading material having with respect to free space a permeability μ and a dielectric constant ϵ , the ratio of μ/ϵ being greater than unity, said line having a geometrical configuration parameter

$$X=\frac{\log \frac{D}{d}}{\log \frac{D_1}{d_1}}$$

where D is the inside diameter of the outer conductor, d is the outside diameter of the inner conductor and D_1

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and d_i are, respectively, the outside and inside diameters of the loading material, said loading material being dimensioned relative to the conducting and dielectric portions of said line in accordance with the expression $X = v(p-q) - q + 1$ where p is the ratio of the permeability of the loading material to that of the dielectric portion of said line, q is the ratio of the dielectric constant of said dielectric portion to that of said loading material and v is equal to

$$\frac{k + 5m + \sqrt{k^2 - 14mk + m^2 + 12m}}{2(1 - 2k - 2m)}$$

where

$$k = \frac{1-q}{p-q} + \frac{Q}{Q'} \frac{p}{p-q} \text{ and } m = \frac{Q}{Q''} \frac{q}{p-q}$$

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Q being the figure of merit of the transmission line without the loading material, Q' being the reciprocal of the magnetic loss tangent of the loading material, and Q'' the reciprocal of the dielectric loss tangent of the loading material.

2. A transmission line as defined in claim 1 wherein the magnetic loading material is ferrite.

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