Dec. 11, 1956 M. ARDITI ET AL 2,774,046

MICROWAVE TRANSMISSION LINE

Filed May 8, 1952 2 Sheets-Sheet 1

Fig.1

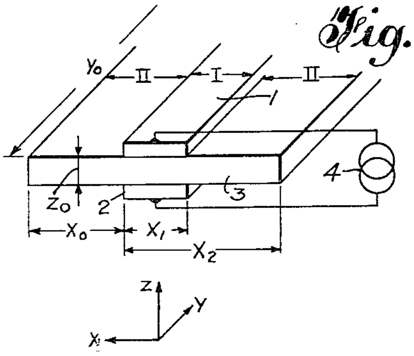


Fig.2

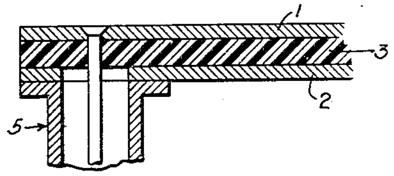
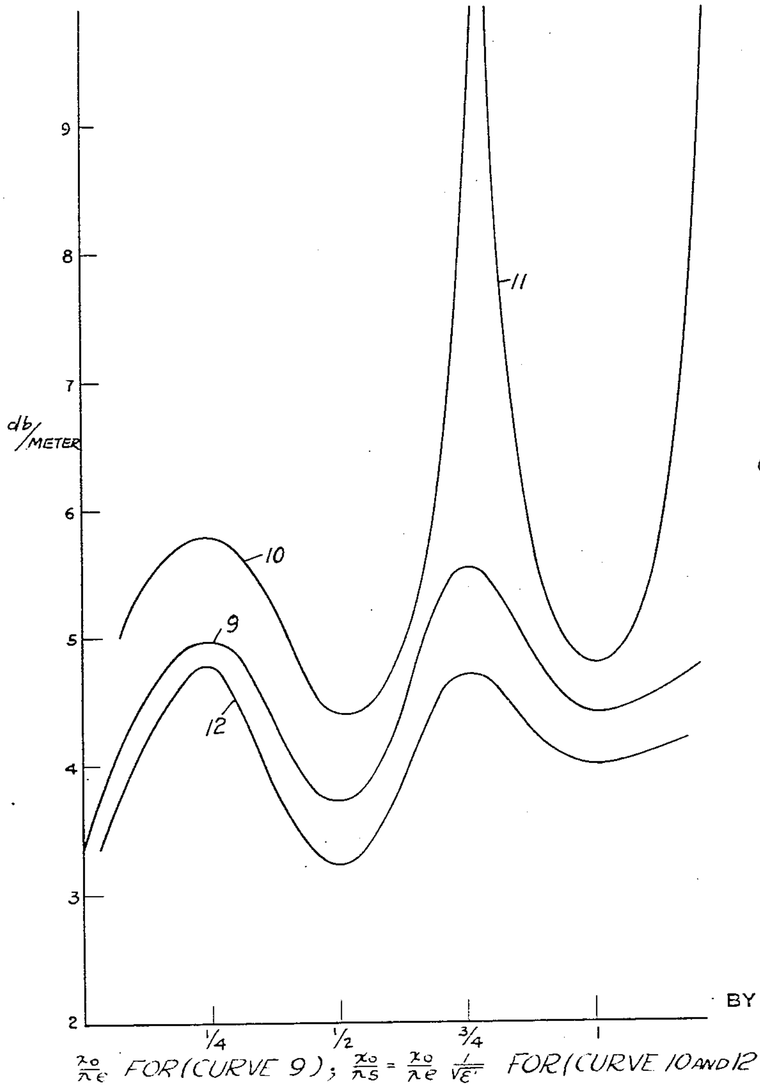


Fig.3



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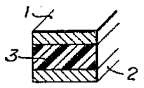
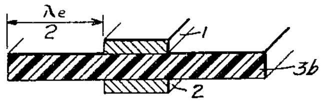


Fig. 4

Fig. 5



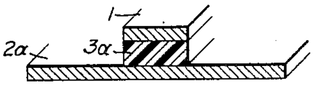
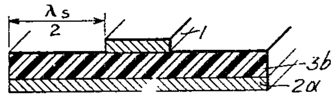


Fig. 6

Fig. 7



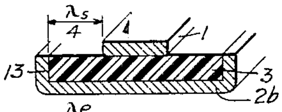
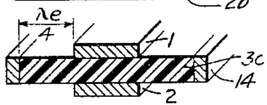


Fig. 8

Fig. 9



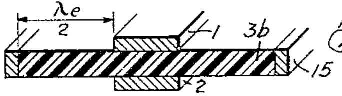
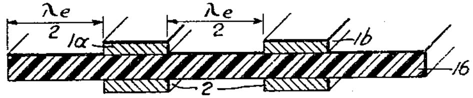


Fig. 10

Fig. 11



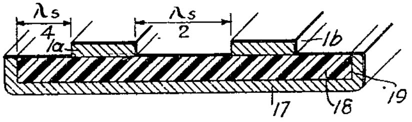
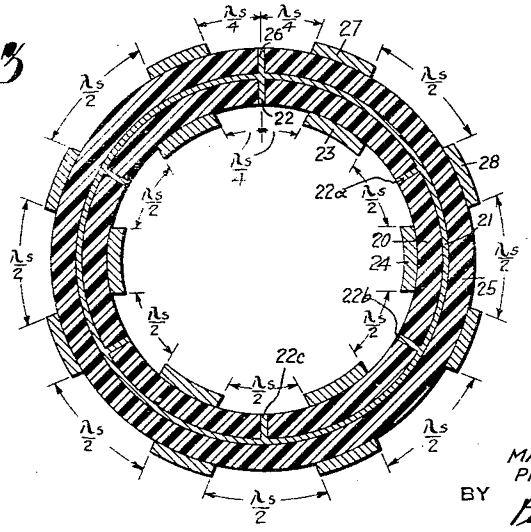


Fig. 12

Fig. 13



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MICROWAVE TRANSMISSION LINE

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Application May 8, 1952, Serial No. 286,764

14 Claims. (Cl. 333—84)

This invention relates to microwave transmission lines and more particularly to a parallel conductor type of line capable of propagating microwave energy in a dominant mode.

In the copending applications of D. D. Greig and H. F. Engelmann, Serial No. 234,503, filed June 30, 1951, now U. S. Patent No. 2,721,312, dated October 18, 1955, a type of microwave transmission line is disclosed comprising in one of its simplest forms two conductors printed or otherwise disposed in substantially parallel relation on opposite sides of a strip or layer of dielectric material a small fraction of a quarter line wavelength thick. While the two conductors may be of the same width it is preferable to have one wider than the other.

One of the objects of this invention is to provide a parallel conductor line of the type above described, wherein the optimum conductor-dielectric relationship is determined to insure wave propagation in a mode simulating essentially the TEM mode.

Another object of the invention is to provide parallel conductor-dielectric type of lines of various conductor-dielectric arrangements wherein the dielectric relationship with respect to the conductors is such as to minimize the excitation of undesired modes from a wave propagated along the line in a TEM mode.

One of the features of the invention is the arrangement of the dielectric between two ribbon-like conductors whereby the conductors are spaced in substantially parallel relation a small fraction of a quarter line wavelength apart and the lateral extent of the dielectric with respect to the line conductor, that is the narrowest of the two conductors, is maintained such as to minimize the excitation of modes of propagation through or over the surface of the dielectric. It is found preferable to limit the dielectric to substantially the width of the line conductor or to extend it therebeyond by an amount equal substantially to an integral number of half wavelengths. This lateral extent of the dielectric strip, however, may be limited to an odd number of quarter wavelengths where the lateral edges of the dielectric are coated with conductive material. If magnetic material is used for coating the lateral edges of the dielectric, then it is preferable to extend the dielectric an integral number of half wavelengths beyond the lateral edges of the line conductor. By following this relationship, a line is obtained over which microwave energy may be propagated in the TEM mode with a minimum of insertion loss. The references to "wavelengths" used herein will best be understood from the following:

(*a*) The free space wavelength in air λ_0 is defined by:

$$\lambda_0=\frac{c}{f}$$

where c is the velocity of light (3×10^{10} cm. per second) and f the frequency in cycles per second.

(*b*) The free space wavelength in the dielectric λ_e

$$\lambda_e=\frac{\lambda_0}{\sqrt{\epsilon'}}$$

where λ_0 is the free space wavelength in air and ϵ' is the real part of the complex dielectric constant ϵ

$$\epsilon=\epsilon'+j\epsilon''$$

(*c*) The surface wavelength λ_s is the wavelength of a TM type wave parallel to the surface of a plane conductor coated with a thin layer of dielectric, usually

$$\lambda_s\leqslant\lambda_0$$

for practical Microstrip lines, for instance

$$\lambda_s\approx0.99\lambda_0$$

For all practical purposes it can be considered that

$$\lambda_s=\lambda_0$$

(*d*) The wavelength of the principal mode propagating in the Microstrip line is called the line wavelength λ_L and

$$\lambda_L=k\lambda_e \text{ with } k\geqslant1$$

k being a function of the dielectric thickness and of the width of the strip conductor

(*e*) The dielectric guide wavelength λ_g for a TM mode excited in a dielectric slab with no ground plane and no strip conductor

$$\lambda_g=\frac{\lambda_e}{\sqrt{1-\frac{n^2\lambda_e^2}{4y_0^2}}}$$

For usual Microstrip lines:

$$\lambda_e y<<4^2 \text{ and } \lambda g\approx\lambda_e$$

(*f*) By comparing Equations (*b*) and (*c*) it can be seen that:

$$\lambda_e=\frac{\lambda_s}{\sqrt{\epsilon'}}$$

It will also be readily apparent that the wavelengths λ_e and λ_s may be referred to by employing "the free space air wavelength" λ_0 as a common basis with the qualification that it is adjusted according to the quality of the dielectric of the strip. For accuracy of disclosure, however, the following detailed description makes reference to the different wavelengths dependent upon the structural arrangement of the conductors and the dielectric strip.

In part (*e*) above the term "*n*" is an integer which expresses the order of the mode, and "y_0" represents the length of the line.

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

Fig. 1 is a view in perspective illustrating one form of transmission line in accordance with the principles of this invention;

Fig. 2 is a longitudinal cross-sectional view showing a coaxial junction for launching a microwave for propagation along the line;

Fig. 3 is a graph of losses of the line shown in Fig. 1 when the dielectric strip is varied in width; and

Figs. 4 through 13 show cross-sectional views of a number of transmission lines made in accordance with the principles of this invention.

Referring to Figs. 1 and 2, the microwave transmission line shown is of the printed circuit type comprising a first or "line" conductor 1 and a second or "base" conductor **2** with a layer **3** of dielectric material therebetween. The conductive material may be applied and/or shaped or etched on a layer of dielectric material, such as polystyrene, polyethylene, "Teflon," fiberglass, quartz, or other suitable material of high dielectric quality, in the form of strips, conductive paint or ink, or the conductive material may be chemically deposited, sprayed through a stencil, or dusted onto selected prepared surfaces of the dielectric, or by any other of the known printed circuit techniques. The spacing of the two conductors is preferably selected a small fraction in the order of about $\frac{1}{10}$ to about $\frac{1}{5}$ of a quarter line wavelength of the microwave propagated therealong.

It is known heretofore that with a transmission line made of two infinite plane parallel conductors a TEM mode may be propagated therealong if properly excited. On the other hand, if one of the conductors is omitted, the propagation of a TM type of wave parallel to the surface of the dielectric can be obtained. When a double conductor micrawave line is printed on a layer of dielectric, it has been found by experiment that a dominant mode having the characteristics of a TEM mode may be obtained along the center portion of the line and that other modes present appear to have the characteristics of a surface wave propagated along the dielectric and in the dielectric space between the conductors. Experiment has shown that there is some coupling between the TEM mode and the surface wave on this type of line. We have found that this coupling can be greatly minimized by properly proportioning the dieletric strip in width with respect to the width of the line conductor **1**. By making the line with the proper conductor-dielectric relationship, insertion losses can be kept to a minimum, it being obvious that surface modes established through or on the surface of the dielectric produce extra high losses. If the transfer of energy can be prevented from the region I, Fig. 1, from being transferred to the region II thereof, the losses can be maintained small. Mathematically, this means that $H_y=H_z=0$ on the dielectric faces. Assuming such to be the case and that microwave energy from source **4**, or a coaxial line **5** coupled to the conductors **1**, **2** as shown in Fig. 2, is applied to the conductors **1** and **2** for propagation therealong, the modes that exist in the region I may be represented as follows:

(*a*) A TEM mode with an E_z and H_x.

(*b*) Those modes which vary with Z. These will be below cut-off if

$$\frac{Z_0}{\lambda_e}<1/2$$

λ_e being the free space wavelength in dielectric.

(*c*) Those modes which vary with *x* only. These modes are:

TE modes:

$$H_y\sim\sin\frac{n\pi x}{x_1}e-\Gamma y$$

$$H_x\sim\cos\frac{n\pi x}{x_1}e-\Gamma y \qquad (1)$$

$$E_z=\cos\frac{n\pi x}{x_1}e-\Gamma y$$

Where $n=1, 2, 3$, etc., e is the natural logarithmic base, and Γy is the propagation constant in the y direction. Such a mode cannot exist since it will be below cut-off for small value of x_1. However, if x_1 is sufficiently large, this mode will propagate and excite fields in region II.

TM modes.—These modes also cannot exist since E_y must vanish for $Z=0$ and $Z=Z_0$.

Thus the only modes are a TEM mode and possibly one TE mode.

Now what are the possible modes in region II?

In view of the great mismatch between the dielectric and air, it is a good approximation to assume that the component of magnetic field parallel to the interface between dielectric and air vanishes. Thus the boundary conditions in region II are:

$$\begin{array}{lll} \text{For } y=0 & y=Y_0 & H_x=H_z=0 \\ Z=0 & Z=Z_0 & H_x=H_y=0 \\ x=x_0 & & H_z=H_y=0 \end{array} \qquad (2)$$

and it is desired to obtain conditions that for

$$x=0,\ H_y=H_z=0.$$

Let us first consider those modes which propagate along the *y* axis. These modes which vary with Z are automatically eliminated as they will not propagate for

$$\frac{Z_0}{\lambda_e}<\frac{1}{2}$$

Those modes which vary with *x* only are:

TE mode:

$$H_y\sim\sin\frac{\pi x}{x_0}e-\Gamma y \qquad (3)$$

This mode cannot exist since H_y must vanish for

$$Z=0$$
$$Z=Z_0$$

TM modes:

$$E_y\sim\cos\frac{n\pi x}{x_0}e-\Gamma y$$

$$E_x\sim\sin\frac{n\pi x}{x_0}e-\Gamma y$$

$$H_z\sim\sin\frac{n\pi x}{x_0}e-\Gamma y \qquad (4)$$

This mode, although it is a propagating mode, will not be excited because it cannot couple to the TEM mode in region I, which possesses only an E_z.

The modes that propagate along the *x* axis in region II are as follows: As previously those modes which vary with Z will not propagate. The other modes are:

TE modes:

$$H_x\sim\sin\frac{n\pi y}{y_0}e-\Gamma x$$

$$H_y\sim\cos\frac{n\pi y}{y_0}e-\Gamma x$$

$$E_z\sim\cos\frac{n\pi y}{y_0}e-\Gamma x \qquad (5)$$

This mode will not propagate since H_y must vanish for $Z=Z_0$ $Z=Z_1$.

TM modes:

$$E_x\sim\cos\frac{n\pi y}{y_0}e-\Gamma x$$

$$E_y\sim\sin\frac{n\pi y}{y_0}e-\Gamma x$$

$$H_z=\sin\frac{n\pi y}{y_0}e-\Gamma x \qquad (6)$$

These are the only modes propagating in region II. The guide wavelength λ_g (in the dielectric) of these modes is given by

$$\lambda_g=\frac{\lambda_e}{\sqrt{1-\frac{n^2\lambda_e^2}{4y_0^2}}} \qquad (7)$$

Now $H_z=0$ for $x=x_0$. Hence $H_z=0$ at $x=0$ if

$$x_0=\frac{m\lambda_g}{2}\ m=0, 1, 2 \qquad (8)$$

Thus the condition that there be no energy flow from region I to region II has been satisfied by choosing properly the width of the dielectric extending beyond the edge of the conductor **1**. Taking $n=1$ and $\lambda_e << 4y0$ this lateral extension is given by

$$x_0=\frac{m\lambda_e}{2} \qquad (9)$$

This theory becomes more accurate as the dielectric constant of the dielectric increases. If the entire bottom of the dielectric is coated with metal, as in Fig. 7, then the propagating mode along the x axis in region II is a surface wave. In this case x_0 should be an integral number of half surface wavelengths

$$\left(\frac{m\lambda_s}{2}=\frac{m\lambda_e\sqrt{\epsilon^1}}{2}\right)$$

of the surface wave if the end faces are uncoated.

Referring more particularly to Fig. 3, the curve therein shown as **9** represents the losses in the line, Fig. 1, as a function of the ratio of the dielectric width to λ_e. It will be observed that the losses were least in the vicinity where $x=0$ or an integral number of

$$\frac{\lambda_e}{2}$$

When a plate was added to the line crosswise of the conductor **1** so as to enhance excitement of multimodes through and on the surface of the dielectric, the losses followed substantially the curve **10** which exceeded the losses of curve **9** until the half wavelength value for x_0 was exceeded and thereafter the losses increased rapidly. This curve **10** is periodic as indicated at **11**. This coupling of the TEM mode of the line in Fig. 1 to other modes such as TE and TM was greatest when the value x_0 equaled

$$\frac{n\lambda_s}{4}$$

where $n=1, 3, 5, \ldots$ or

$$\frac{n\lambda_e\sqrt{\epsilon'}}{4}$$

where $n=1, 3, 5 \ldots$ This also was substantiated by the curve **9** in the absence of the coupling plate. It is to be understood that the results illustrated by the curves of Fig. 3 represent the losses of a region of an infinite line far removed from the junction coupling wave energy thereto.

Referring to Figs. 4 through 13, various line constructions are illustrated wherein a minimum of multimode coupling and, therefore, a minimum of line loss may be experienced. In Fig. 4 the two conductors **1** and **2** are separated by dielectric **3*a*** where the value $x_0=0$. This form of line is found to give low losses as indicated by the curve **9**. It was noted that when the dielectric strip **3*a*** was made narrower than the line conductor the line losses seemed to increase thereby indicating a possible increase of field concentration in the dielectric or excitation of undesired modes. In Fig. 5 the dielectric **3*b*** is shown to have a value such that

$$x_0=\frac{\lambda_e}{2}$$

The losses for this type of line is illustrated for the first dip in the curve **9**. Fig. 6 shows another embodiment similar to the form shown in Fig. 4 wherein the base conductor **2*a*** is considerably wider than the conductor **1** or the dielectric **3*a***. This extent of the conductor **2*a*** decreases slightly the losses experienced in the form shown in Fig. 4. In Fig. 7 the line is shown wherein the dielectric **2*b*** extends to an amount such that

$$x_0=\frac{\lambda_s}{2}$$

The conductor **2*a*** is also of the same width. This form of line showed even less losses than the line illustrated in Fig. 4. The extent of the dielectric **2*b*** appeared to minimize the excitation of dielectric wave modes. It was

believed that the extended dielectric presents a greater attenuation to the excitation of such modes in this form. The losses experienced in this form of line are illustrated by the curve **12**, Fig. 3.

In Fig. 8 the dielectric strip is shown to have about half the extent of that illustrated in Fig. 7, that is, a value such that

$$x_0=\frac{\lambda_s}{4}=\frac{\lambda_e\sqrt{\epsilon'}}{4}$$

By extending the base conductor **2*b*** around the side edges of the dielectric **3*c***, as indicated at **13**, a line characteristic may be obtained substantially as that obtained in the form of Fig. 7. In Fig. 9, a similar relationship

$$x_0=\frac{\lambda_e}{4}$$

is obtained even where conductors **1** and **2** are the same as in Figs. 1, 4, and 5, with the exception that additional layers of conductive material **14** is placed on the lateral side edges of the dielectric **3*c***. It was also found that a similar line effect could be obtained wherein the dielectric has an extent such that the value

$$x_0=\frac{\lambda_e}{2}$$

if magnetic material is applied to the side edges of the dielectric. Such a line is shown in Fig. 10. There the dielectric **3*b*** is provided with a layer of magnetic material **15** on the lateral side edges, the magnetic material being preferably of very high magnetic permeability, such as "Ferrite."

The double line illustrated in Fig. 11 is similar to the form shown in Fig. 5 except that the space between adjacent conductors **1*a*** and **1*b*** is equal substantially to

$$\frac{\lambda_e}{2}$$

Likewise, the dielectric **16** thereof is extended laterally of the line conductors on the free sides thereof by an amount corresponding to

$$\frac{\lambda_e}{2}$$

The base conductors **2** may be identical to the line conductors **1*a*** and **1*b*** or if desired may extend the full width of the dielectric **16**. In Fig. 12, for example, the base conductor **17** is shown to extend crosswise of the dielectric **18** and also along the lateral sides thereof as indicated at **19**. The space between the line conductors **1*a*** and **1*b*** will now correspond to

$$\frac{\lambda_s}{2}=\frac{\lambda_e\sqrt{\epsilon'}}{2}$$

and the spacing between the outer edge of the line conductor and the conductive portions **19** corresponds to

$$\frac{\lambda_s}{4}=\frac{\lambda_e\sqrt{\epsilon'}}{4}$$

An extension of the multichannel cable of Fig. 12 is shown in Fig. 13. Two such multichannel strips are formed back to back into a cylindrical cable. The cylindrical cable comprises one such strip **20** coated on one side with a layer of conductive material **21** and between the abutting edges, as indicated at **22**. The line conductors are disposed on the other surface of the dielectric strip **20**, as indicated at **23** and **24**. The spacing between the conductor portion **22** of the base conductor and the next adjacent line conductors corresponds to

$$\frac{\lambda_s}{4}$$

The spacing between adjacent line conductors, such as **23** and **24**, corresponds to

$$\frac{\lambda_s}{2}$$

This much of the cylindrical cable could comprise a finished cable wherein the coating 21 may comprise a copper braid coated with dielectric and the usual protective jacket. It is important, however, that a break be made in the dielectric strip 20 so as to provide either an air gap or a lateral conductor, such as indicated at 22. Such an air gap or groove in the dielectric strip provides a desired dielectric-to-air mismatch impedance to minimize multimoding and the possibility of interchannel coupling or crosstalk. Such air gap or conductive partition may be provided in the dielectric strip between adjacent channels, if desired. Such provision of air gaps or partitions provide additional shielding between adjacent channels. The strip 20 is accordingly shown provided with such partitions at *22a*, *22b*, and *22c*.

In the embodiment shown in Fig. 13, the cable is also shown to comprise a second layer of dielectric 25 having a partition 26. The same copper braid or other conductive coating 21 may serve as the base conductor for both sections. On the outer surface of the dielectric strip 25 are disposed a plurality of independent line conductors, such as indicated at 27 and 28. Here again the spacing between the conductive partition 26 and the next adjacent line conductors, such as 27 is in accordance with

$$\frac{\lambda_s}{4}$$

The spacing between adjacent line conductors, such as 27 and 28, is according to

$$\frac{\lambda_s}{2}$$

If desired, such a cable may be further coated with dielectric and a suitable jacket. It is preferable, however, that the line conductors be provided with an air space adjacent thereto to insure low insertion losses.

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

We claim:

1. A transmission cable for propagation of a plurality of radio frequency wave channels in a dominately TEM mode comprising a base conductor of tubular form, a layer of dielectric disposed on one side of said tubular conductor, a plurality of line conductors disposed on said dielectric layer, said line conductors being substantially parallel to each other and spaced apart substantially one half a surface wavelength, and said base conductor having at least one conductive strip disposed radially thereof through said dielectric at a point spaced substantially halfway between two adjacent line conductors.

2. A transmission cable according to claim 1, wherein said dielectric layer is disposed on the inside surface of said tubular conductor.

3. A transmission cable according to claim 1, wherein the dielectric layer is disposed on the outer surface of said tubular conductor.

4. A transmission cable according to claim 1, wherein said base conductor includes a plurality of conductive strips extending through the dielectric, one each halfway between adjacent ones of said line conductors.

5. A transmission cable for propagation of a plurality of radio frequency wave channels in a dominately TEM mode comprising a base conductor of tubular form, a layer of dielectric disposed on the inside surface of said tubular conductor, a plurality of line conductors disposed on said dielectric layer, said line conductors being substantially parallel to each other and spaced apart substantially one half a surface wavelength, a second layer of dielectric material disposed on the outside surface of said base conductor, and a plurality of line conductors disposed in substantially parallel relation on the outer surface of said second layer of dielectric spaced apart substantially one half a surface wavelength, and said base conductor having conductive strips disposed radially one each through each of the layers of dielectric.

6. A transmission line for propagation of radio frequency wave energy in a mode simulating substantially the TEM mode, comprising a pair of conductors, a strip of dielectric material separating said conductors in closely spaced substantially parallel relation, the mutually opposed surfaces of said conductors having a lateral extent corresponding substantially to the width of at least one of said conductors and said dielectric strip being of a width greater than said one conductor such that each of its lateral edges extends beyond the corresponding lateral edge of said one conductor by an amount equal substantially to an integral number of quarter wavelengths of the free space air wavelength adjusted according to the quality of the dielectric of said strip at which excitation of wave modes through or over the surface of the dielectric is minimized, plus an integral number, including zero, of such adjusted wavelengths divided by two.

7. A transmission line according to claim 6, wherein the lateral edges of said dielectric are bounded by a nonconductive medium and said given fraction of the free space air wavelength is one-half.

8. A transmission line according to claim 6, wherein said dielectric strip carries an electrically conductive layer at the lateral edges thereof and said given fraction of the free space air wavelength is one-quarter.

9. A transmission line according to claim 6, wherein said dielectric strip carries a layer of ferromagnetic material of high permeability on the lateral edges thereof.

10. A transmission line according to claim 6, wherein said strip is extended laterally and said conductors are multipled at least on one side of said strip to provide a plurality of channels, the lateral spacing between the conductors of said adjacent channels corresponding substantially to a half of one of said adjusted wavelengths or an integral multiple thereof.

11. A transmission line according to claim 6, wherein said given fraction of the free space air wavelength is one-quarter and the width of the other of said conductors is equal to substantially the width of said dielectric strip, said dielectric strip carrying on the lateral edges thereof a layer of conductive material as continuations of said other conductor.

12. A transmission line according to claim 11, wherein said one conductor is multipled to form a plurality of separate line conductors with the spacing between adjacent line conductors equal substantially to a half of one of said adjusted wavelengths or an integral multiple thereof to minimize excitation of wave modes through or over the surface of the dielectric adjacent each of said line conductors.

13. A transmission line according to claim 12, wherein the strip of dielectric is of tubular shape with the line conductors on one side of said tubular strip and said other conductor is on the other side thereof, the conductive material being disposed on the lateral edges of the dielectric strip comprising a conductive partition in the dielectric tubing.

14. A transmission line according to claim 12, further including a conductive partition extending from said other conductor through the dielectric strip substantially half way between adjacent line conductors.

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