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COMPOSITE CONDUCTOR

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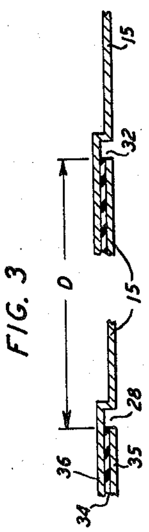

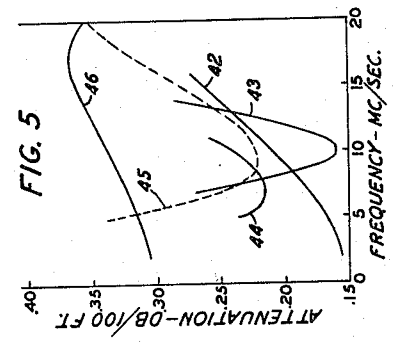

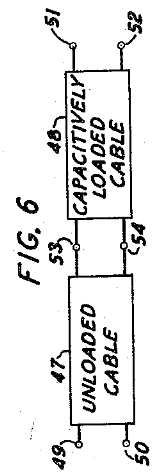

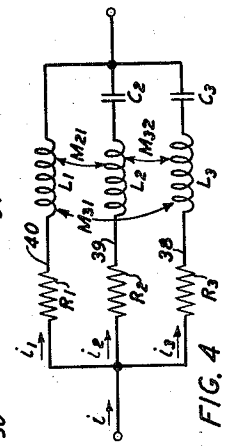

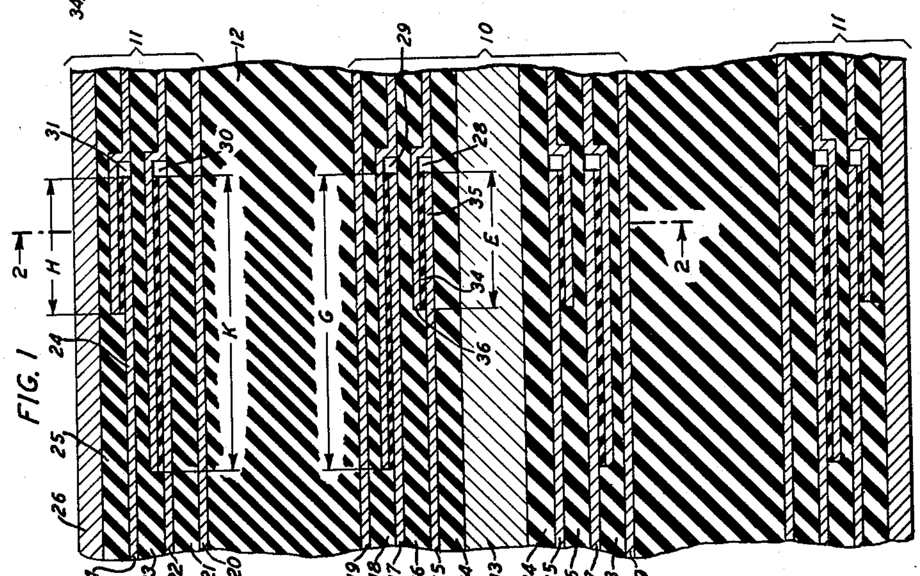

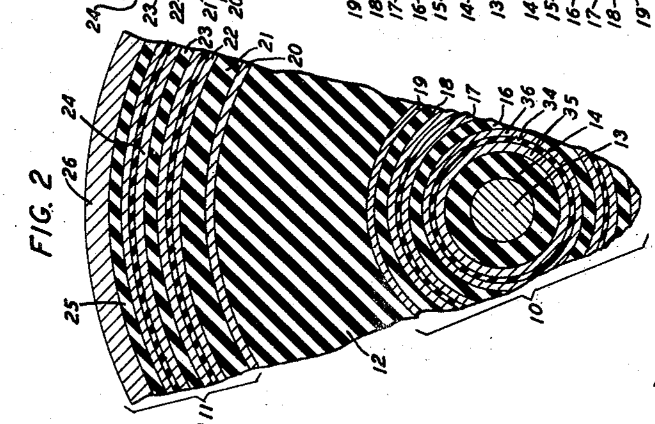

INVENTOR
J. M. EGLIN
BY
Ralph P. Holcomb
ATTORNEY

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COMPOSITE CONDUCTOR

James M. Eglin, Glen Rock, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

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This invention relates to high-frequency electrical conductors and more particularly to composite conductors formed of a plurality of spaced conducting laminae or layers.

An object of the invention is to improve the current distribution in a laminated conductor in order to decrease or flatten the effective resistance of the conductor over a selected band of frequencies. Other objects are to lower or flatten, over a selected band, the attenuation of a transmission line comprising such a conductor.

In a wave transmission line such, for example, as a coaxial cable having an inner conductor and a concentric outer conductor, it is known that ordinarily the attenuation of alternating currents transmitted therethrough is dependent upon the resistance of the cable and increases with frequency. At the higher frequencies an important cause of this increase in resistance and attenuation is the fact that the currents tend to concentrate at the outer surface of the inner conductor and at the inner surface of the outer conductor.

In accordance with the embodiment of the present invention disclosed herein by way of example, the attenuation in such a cable, over a selected band of frequencies, is reduced or flattened by constructing one or both of the conductors of a plurality of comparatively thin, spaced, coaxial, conducting layers, dividing transversely one or more of the layers into sections which are short compared to a wavelength within the cable at a selected frequency, and connecting the sections in each layer by series capacitances so chosen that the distribution of currents between the layers is more advantageous. One way of obtaining an advantageous distribution is to choose the capacitances so that the currents in the various layers are approximately in phase at the selected mid-band frequency or at one or more selected frequencies above and below the mid-band. In this way, the effective resistance is decreased or flattened and the attentuation of the cable is reduced or made more uniform throughout the band. Reducing the attenuation increases the efficiency of signal transmission. Flattening the attenuation in the band simplifies the equalization problem.

In the embodiments disclosed, the series capacitance is obtained by overlapping the ends of adjacent sections in a layer and inserting a layer of dielectric material between the overlapping portions. If the layers of a conductor are of the same thickness and are equally spaced, the effective inductance of the layer will increase, and, therefore, in order to get the desired phase relationship, the required magnitude of the added series capacitances will decrease, as the distance of the layer from the surface nearest the return conductor increases. The width of the flattened transmission band may be increased by so choosing the values of the added capacitances that the currents in two or more layers in the same or different conductors are in phase with the current in a reference layer at different frequencies.

Over a preselected frequency range, the attenuation

characteristic of a capacitance-loaded cable of the type described will have a negative slope. In accordance with an extension of the invention, a section of such a cable is connected in tandem with a section of transmission line having an attenuation characteristic with a complementary positive slope. The over-all attenuation of the two sections is made more uniform over a considerable frequency range.

The nature of the invention and its various objects, features, and advantages will appear more fully in the following detailed description of preferred embodiments illustrated in the accompanying drawing, of which:

Fig. 1 is a longitudinal section through the center of a coaxial cable employing laminated, capacitively loaded, inner and outer conductors in accordance with the invention;

Fig. 2 is a sector of a transverse section of the cable taken at the line **2—2** of Fig. 1;

Fig. 3 is a longitudinal sectional view of a portion of a conducting layer, with an intermediate part thereof omitted, showing the spacing D of the series capacitors;

Fig. 4 is a schematic circuit used in explaining how the values of the loading capacitances are determined;

Fig. 5 presents attenuation versus frequency characteristics showing the improvement obtainable with capacitance-loaded cables in accordance with the invention; and

Fig. 6 shows in block diagram the tandem combination of a section of unloaded cable and a section of capacitively loaded cable having complementary transmission characteristics over a band of frequencies.

Taking up the figures in greater detail, the coaxial cable in accordance with the invention shown in Figs. 1 and 2 comprises a laminated inner conductor **10**, a laminated outer conductor **11** coaxial therewith, and interposed dielectric material **12**. The inner conductor **10** is made up of a central core **13**, which may be either a conductor or a non-conductor, a plurality of cylindrical conducting layers **15**, **17**, and **19** surrounding the core **13**, and interposed layers **14**, **16**, and **18** of insulating material. The outer conductor **11** consists of a plurality of coaxial cylindrical conducting layers **20**, **22**, and **24**, a surrounding sheath **26** of metal or other suitable shielding material, and interposed layers **21**, **23**, and **25** of insulating material. The conducting layers such as **15** and **24** are preferably thin compared to the skin depth of the material which, for example, may be copper or aluminum.

Each of the conducting layers **15**, **17**, **22**, and **24** is divided transversely, as shown at the points **28**, **29**, **30**, and **31**, respectively, into sections which are short compared to a wavelength λ within the cable at a selected frequency f. The length D of a section of the layer **15** between the successive points of division **28** and **32** is indicated on Fig. 3. Preferably, D is less than $\lambda/4$.

The sections of each conducting layer are connected by series capacitances which are formed by overlapping the ends of adjoining sections. As shown in Fig. 1, the sections of the innermost conducting layer **15** of the inner conductor **10** overlap for a distance E. A layer **34** of dielectric material is inserted between the overlapping portions **35** and **36**. The layer **34** may, for example, be a very thin film of polyethylene or a somewhat thicker film of a material having a higher dielectric constant, such as a composition comprising polystyrene, dichlorostyrene, and titanium oxide. In the layer **17**, the sections overlap for a somewhat greater distance G. In the outer conductor **11**, the length of overlap in the outermost segmented layer **24** is H and in the layer **22** it is K, which usually is greater than H. The insulating layers such as **16** and **23** should be as thin as possible except that the capacitance between layers in a length D is preferably small compared to the series capacitance introduced in that length.

A suggested method of determining the required values of the loading capacitances will now be presented with the aid of Fig. 4, which shows schematically the equivalent circuit representing a section of the conducting layers **15**, **17**, and **19** in the inner conductor **10**. The circuit comprises three parallel branches **38**, **39**, and **40** which represent, respectively, the layers **15**, **17**, and **19**. Each of the branches consists of a series combination of elements. In the branch **40** these elements are a resistance R_1 and an inductance L_1, in the branch **39** they are R_2, L_2, and a capacitance C_2, and in the branch **38** they are R_3, L_3, and C_3. The resistances R_1, R_2, and R_3 are the resistances per section of the three layers and L_1, L_2, and L_3 are the series self-inductances per section. In addition, there are mutual inductances per section indicated by M_{21}, M_{31}, and M_{32}. The loading capacitances per section of the layers **17** and **15** are represented, respectively, by C_2 and C_3. The inductances will increase in value as the distance of the layer from the outer surface of the inner conductor **10** increases. Therefore, L_2 will be larger than L_1, and L_3 larger than L_2.

Since the voltage drop e is the same in each of the three branches, we may write the following equations:

$$e=R_1i_1+j\omega L_1i_1+j\omega M_{21}i_2+j\omega M_{31}i_3 \quad (1)$$
$$e=R_2i_2+j\omega M_{21}i_1+j(\omega L_2-1/\omega C_2)i_2+j\omega M_{32}i_3 \quad (2)$$
$$e=R_3i_3+j\omega M_{31}i_1+j\omega M_{32}i_2+j(\omega L_3-1/\omega_3)i_3 \quad (3)$$

where ω is the radian frequency $2\pi f$ and i_1, i_2, and i_3 are the currents in the branches **40**, **39**, and **38**, respectively.

For this illustrative analysis, it will be assumed that each of the branches has the same resistance, R, at the frequency f, that is, that

$$R_1=R_2=R_3=R \quad (4)$$

It will also be assumed that the layers **15**, **17**, and **19** are thin enough that the mutual inductance between any two layers may be considered to be equal to the self-inductance of one of them, that is, that

$$M_{21}=M_{31}=L_1 \quad (5)$$

and

$$M_{32}=L_2 \quad (6)$$

Substituting these values of the mutual inductances in Equations 1, 2, and 3 leads to the following expressions:

$$e-j\omega L_1(i_1+i_2+i_3)=Ri_1 \quad (7)$$
$$e-j\omega L_1(i_1+i_2+i_3)=Ri_2+j[\omega(L_2-L_1)-1/\omega C_2]i_2+j\omega(L_2-L_1)i_3 \quad (8)$$
$$e-j\omega L_1(i_1+i_2+i_3)=Ri_3+j\omega(L_2-L_1)i_2+j[\omega(L_3-L_1)-1/\omega C_3]i_3 \quad (9)$$

The ohmic resistance R_0 of the three branches **38**, **39**, and **40** in parallel is the real part of the ratio of the voltage e to the total current i. The current i is the sum of the currents in the branches, that is,

$$i=i_1+i_2+i_3 \quad (10)$$

From Equation 7, e is

$$e=Ri_1+j\omega L_1i \quad (11)$$

Therefore,

$$R_0=\text{Real part of } Ri_1/i \quad (12)$$

We now define Δ as the different between the inductances L_2 and L_1, that is,

$$L_2-L_1=\Delta \quad (13)$$

Now, assuming that the layers **15**, **17**, and **19** are equally spaced, the difference between the inductances L_3 and L_1 will be approximately 2Δ, that is,

$$L_3-L_1\doteq 2\Delta \quad (14)$$

Since the left sides of Equations 7, 8, and 9 are all equal, we may equate the right side of 7 to the right sides of 8 and 9, respectively, to get the following two independent expressions for Ri_1:

$$Ri_1=Ri_2+j[\omega L_2-L_1)-1/\omega C_2]i_2+j\omega(L_2+L_1)i_3 \quad (15)$$
$$Ri_1=Ri_3+j\omega(L_2-L_1)i_2+j[\omega(L_3-L_1)-1/\omega C_3]i_3 \quad (16)$$

Substituting in Equations 15 and 16 the values of the differences between the inductances as given in Equations 13 and 14 gives

$$Ri_1=[R+j(\omega\Delta-1/\omega C_2)]i_2+j\omega\Delta i_3 \quad (17)$$

and

$$Ri_1=j\omega\Delta i_2+[R+j(2\omega\Delta-1/\omega C_3)]i_3 \quad (18)$$

If the frequency f is selected and R, L_1, and L_2 are known, Equations 17 and 18 may be used to find R_0 in terms of C_2 and C_3.

Since the attenuation of the structure is substantially proportional to the resistance R_0, it follows that the attenuation may be minimized by minimizing R_0. The values of C_2 and C_3 which make R_0 a minimum can be found by the usual procedures of differentiation of the expression for R_0. The resulting values are

$$C_2=\tfrac{1}{2}\omega^2\Delta \quad (19)$$

and

$$C_3=\tfrac{1}{3}\omega^2\Delta \quad (20)$$

When these values of C_2 and C_3 are substituted in Equations 17 and 18, it is found that, in this case, the branch currents are equal. That is,

$$i_1=i_2=i_3 \quad (21)$$

This condition may be described as making the effective reactances of the branches **38**, **39**, and **40** equal, at the frequency f, by proper choices of the loading capacitances C_2 and C_3.

If the branch resistances R_1, R_2, and R_3 are unequal, by following a procedure similar to the one outlined above it is found that the following relationships are required for minimum attenuation at a selected frequency:

$$R_1i_1=R_2i_2=R_3i_3 \quad (22)$$

In this case, although the branch currents need not be equal in magnitude, they are equal in phase.

The examples just given are illustrative of the general procedure to be employed in practicing the invention. Other desired objectives may be attained. For example, it may be desired to flatten the resistance over a considerable range of frequencies, instead of minimizing R_0 at the particular frequency f. In this case, if there are three layers **15**, **17**, and **19** as shown, I have found that C_2 should have a larger value than given by Equation 19 and C_3 a smaller value than given by Equation 20. The currents i_1, i_2 and i_3 will no longer be equal in magnitude or phase at the same frequency. The process can be described as reducing the effective reactance of each of the branches **38** and **39** at a different frequency, one higher than f and the other lower than f. The currents i_1 and i_2 are thus in phase at a frequency on one side of f and the currents i_1 and i_3 are in phase at a frequency on the other side of f.

The required values of the loading capacitances to be used in the outer conductor **11** are found in a similar manner. In this case, the branches **38**, **39**, and **40** of the equivalent circuit will represent, respectively, the conducting layers **24**, **22**, and **20**.

In Fig. 5, the solid-line curve **42** is a typical attenuation versus frequency characteristic of a laminated coaxial cable of the type described when the loading capacitances are omitted and the conducting layers are continuous and in contact throughout. The attenuation increases with frequency in a well-known manner. The curve **43** shows the improved characteristic obtainable with a cable in accordance with the invention, such as is illustrated in Figs. 1 and 2, when both the inner conductor **10** and the outer conductor **11** are capacitively loaded and a frequency f of ten megacycles per second is used in computing the values of the capacitances. It is seen that the attenuation is considerably lowered, and, therefore, the efficiency of transmission is improved, over a band of frequencies approximately centered at f.

The curves **44** and **45** of Fig. 5 show the types of attenuation characteristics obtainable by staggering the frequencies for which the loading capacitances are selected. For the curve **44**, the resistance shaping for each of the conductors **10** and **11** was alike, but in each conductor different frequencies were selected for the two individual conducting layers such as **15** and **17** or **22** and **24**. For the broken-line curve **45**, on the other hand, the frequencies selected for the individual conducting layers in each of the conductors **10** and **11** were alike, but frequencies of 7.5 and 12.5 megacycles, respectively, were employed for the two conductors. As compared with the curve **43**, it is seen that each of the characteristics **44** and **45** has a somewhat higher attenuation but a considerably wider transmission band.

Fig. 6 shows an extension of the invention in which a section of unloaded cable **47** is connected in tandem with a section of capacitively loaded cable **48** to flatten the band over a considerable range of frequencies. The sections are connected between a pair of input terminals **49**, **50** and a pair of output terminals **51**, **52**, with intermediate common terminals **53**, **54**. The unloaded cable **47** has an attenuation characteristic of the type shown by the curve **42** of Fig. 5, with a positive slope throughout. The loaded cable **48** may, for example, be of the type shown in Figs. 1 and 2. As shown by the typical curves **43**, **44**, and **45**, its attenuation characteristic has a negative slope below the transmission band. The section **48** is so designed that, over a selected range of frequencies, its characteristic has a negative slope which is substantially complementary to that of the section **47**. The over-all attenuation characteristic of the two sections connected in tandem will thus be substantially flat over an extended frequency range, as shown by the curve **46**.

Although in the embodiment of the invention shown in Figs. 1 and 2 each of the conductors **10** and **11** employs two sectionalized, capacitively loaded conducting layers, it is to be noted that a considerable improvement is to be obtained by using only one such layer in each conductor or in only one conductor. Of course, more than two such layers may be used, and the employment of more than two layers in each conductor is often justified economically. The arrangements described herein are to be considered only as illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A conductor adapted to carry high-frequency currents comprising two conducting layers separated by insulation, one of said layers being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, and lumped series capacitances connecting said sections, each of said capacitances being large compared to the capacitance between one of said sections and the other layer, said layers having different effective series inductances, and said series capacitances being so chosen that the currents transmitted through said layers are in phase at said frequency.

2. A high-frequency conductor comprising two conducting layers separated by insulation, one of said layers being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, and lumped series capacitances connecting said sections, each of said capacitances being large compared to the capacitance between one of said sections and the other layer, and said series capacitances being chosen to lower the resistance of the conductor at said frequency.

3. A high-frequency conductor comprising two conducting layers separated by insulation, one of said layers being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, and lumped series capacitances connecting said sections, each of said capacitances being large compared to the capacitance between one of said sections and the other layer, and said series capacitances being chosen to make the resistance of the conductor more uniform over a band of frequencies.

4. A high-frequency conductor comprising two conducting layers separated by insulation, each of said layers being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, and lumped series capacitances connecting said sections in each of said layers, each of said capacitances being large compared to the capacitance between one of said sections and the other layer, said series capacitances being chosen to lower the resistance of the conductor at said frequency, and the series capacitance per unit length of said layers decreasing with the distance of the layer from a boundary of said conductor.

5. A cable adapted to transmit high-frequency currents comprising an inner conductor and an outer conductor coaxial therewith, each of said conductors comprising two conducting layers with interposed insulation, one of said layers in each of said conductors being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, and lumped series capacitances connecting said sections in each of said individual layers, each of said capacitances being large compared to the capacitance between one of said sections and an adjacent layer, said layers in each of said conductors having different effective series inductances, and said capacitances being so chosen that in each of said conductors the currents transmitted through each of said layers are approximately in phase at said frequency.

6. A cable for the transmission of electromagnetic waves comprising an inner conductor and a tubular outer conductor coaxial therewith, each of said conductors comprising a plurality of concentric, thin-walled, conducting layers separated by insulation, each of said layers being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, and lumped series capacitances connecting the sections in each of said layers, each of said capacitances being large compared to the capacitance between one of said sections and an adjacent layer, and in each of said conductors the series capacitance per section of said layers decreasing with the distance of the layer from the boundary of the conductor opposed to the other of said conductors.

7. A cable for the transmission of electromagnetic waves comprising an inner conductor and a tubular outer conductor coaxial therewith, one of said conductors comprising a plurality of concentric, thin-walled, conducting layers separated by insulation, each of said layers being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, and lumped series capacitances connecting the sections in each of said layers, each of said capacitances being large compared to the capacitance between one of said sections and an adjacent layer, and two of said layers having equal reactances at different frequencies so chosen that the transmission band of the cable is widened.

8. A cable for the transmission of electromagnetic waves comprising an inner conductor and a tubular outer conductor coaxial therewith, each of said conductors comprising a plurality of concentric, thin-walled, conducting layers separated by insulation, one of said layers in each of said conductors being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, and lumped series capacitances connecting the sections in each of said sectionalized layers, each of said capacitances being large compared to the capacitance between one of said sections and an adjacent layer, and said sectionalized layer in said inner conductor and said sectionalized layer in said outer conductor hav-

ing equal reactances at different frequencies so chosen that the transmission band of the cable is widened.

9. A conductor adapted to transmit high-frequency currents comprising three thin conducting layers separated by insulation, two adjacent ones of said layers being divided transversely into sections which are short compared to a wavelength at a transmitted frequency f, and lumped series capacitances connecting the sections in each of said divided layers, each of said capacitances being large compared to the capacitance between one of said sections and an adjacent layer, adjacent ones of said layers having effective series inductances per section which differ by Δ, the series capacitance per section of one of said divided layers being approximately equal to $\frac{1}{2}\omega^2\Delta$, and the series capacitance per section of the other of said divided layers being approximately equal to $\frac{1}{3}\omega^2\Delta$, where ω is $2\pi f$.

10. A composite elongated electromagnetic wave conductor adapted for use with high-frequency electromagnetic waves comprising two thin conducting layers separated by insulation, one of said layers being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, adjacent ends of said sections overlapping to provide lumped series capacitances effective between the sections, each of said capacitances being large compared to the capacitance between one of

said sections and the other layer, said layers having different series inductances, and said series capacitances being so chosen that the currents transmitted through said layers are in phase at said frequency.

11. A cable adapted for use with high-frequency electromagnetic waves comprising an inner conductor and an outer conductor coaxial therewith, one of said conductors comprising two thin conducting layers with interposed insulating material, one of said layers being divided transversely into sections which are short compared to a wavelength at a transmitted frequency, adjacent ends of said sections overlapping to provide lumped series capacitances effective between the sections, each of said capacitances being large compared to the capacitance between one of said sections and the other layer, said layers having different series inductances, and said series capacitances being so chosen that the currents transmitted through said layers are in phase at said frequency.

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