United States Patent

Foley

[15] **3,659,232**

[45] **Apr. 25, 1972**

[54] TRANSMISSION LINE FILTER

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[73] Assignee: **RCA Corporation**

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[21] Appl. No.: **13,316**

[52] **U.S. Cl.** .....**333/73 C**, 333/79

[51] **Int. Cl.** **H03h 1/10**

[58] **Field of Search** .....333/9, 73 C, 73 W

[56] **References Cited**

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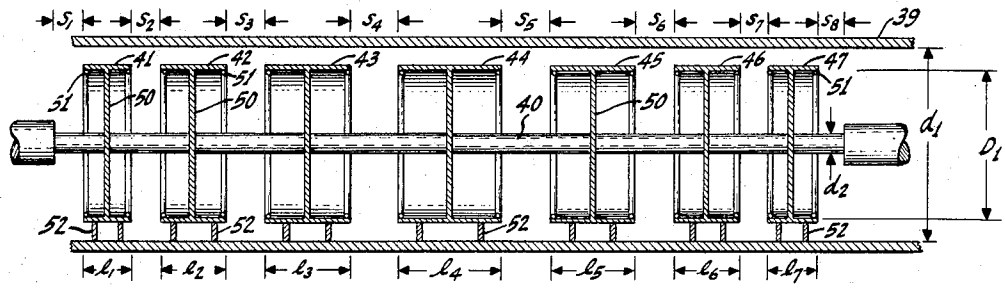
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[57] **ABSTRACT**

A coaxial transmission line filter wherein open end cylindrical conducting elements, having equal diameters and various lengths and spacings, are provided for suppressing at least one spurious pass band in the frequency response of the filter.

5 Claims, 7 Drawing Figures



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SHEET 1 OF 2

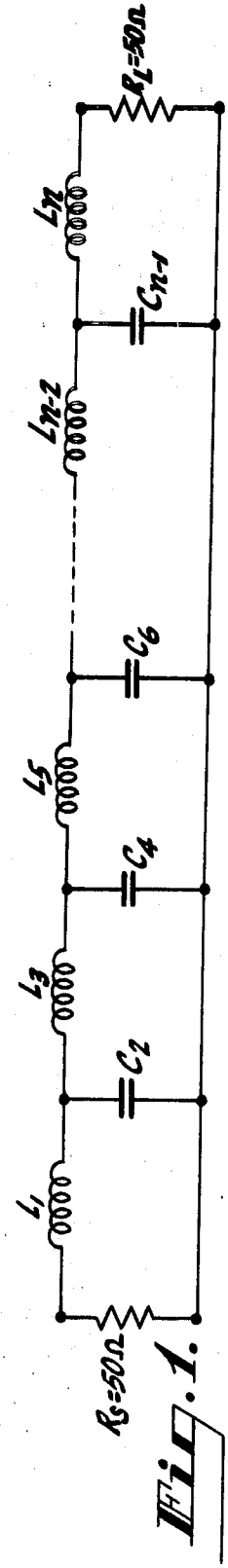


Fig. 1.

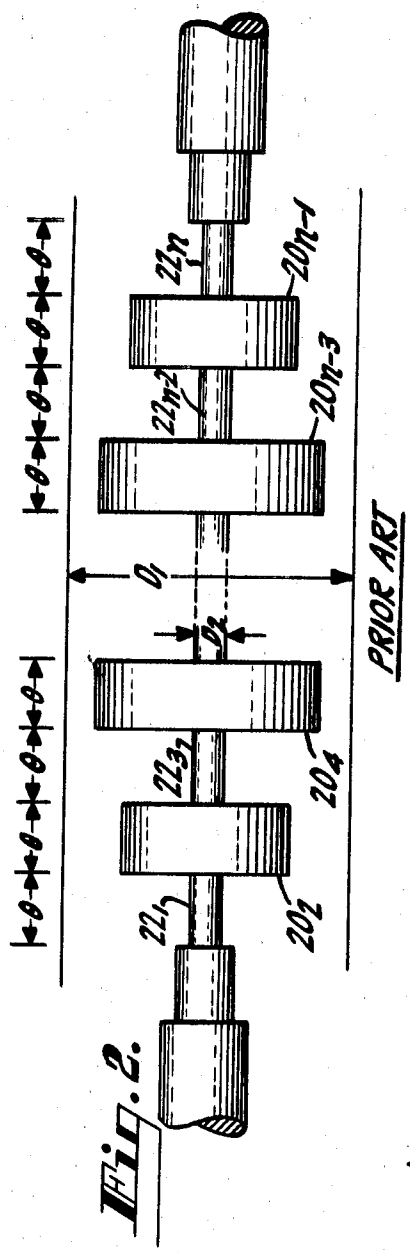


Fig. 2.

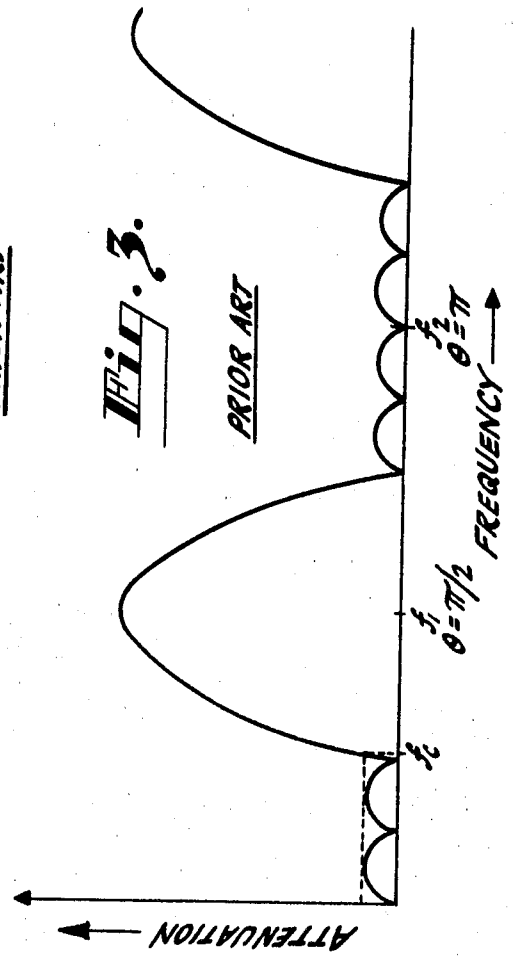


Fig. 3.

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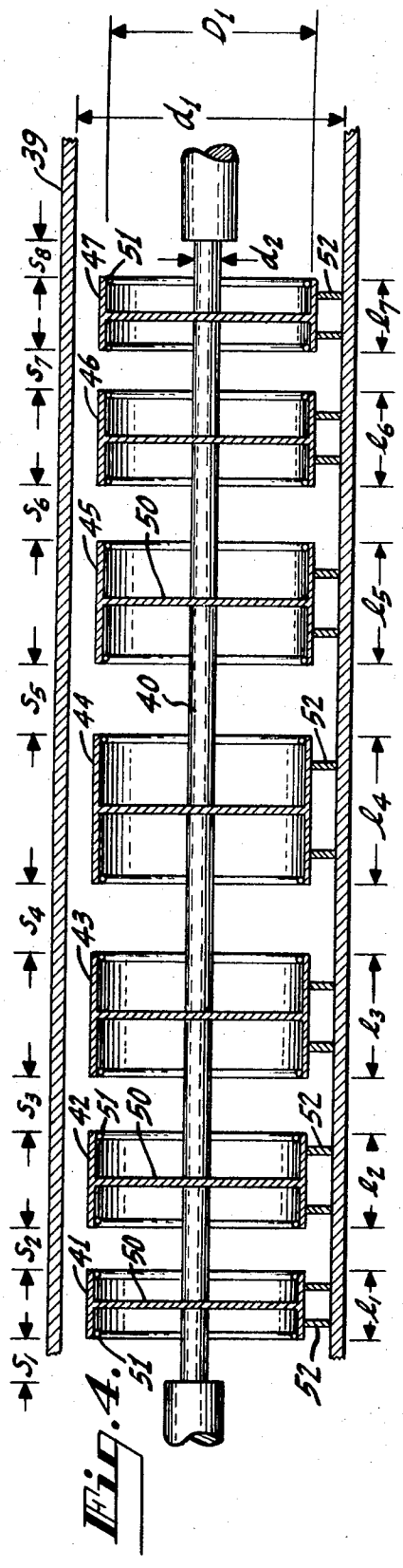


Fig. 4.

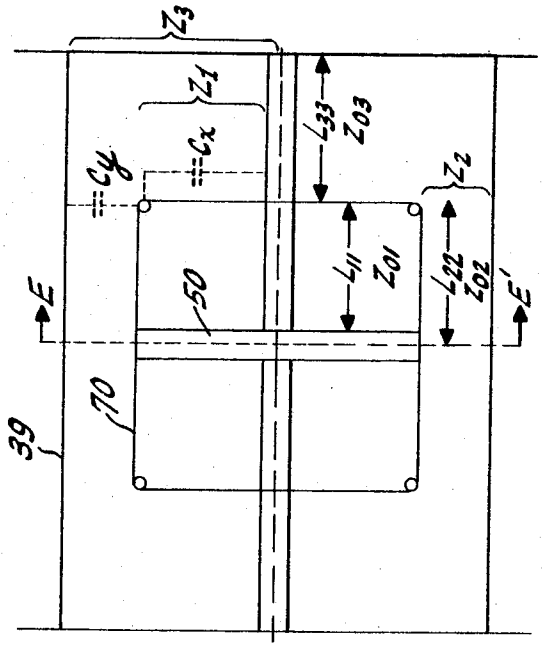


Fig. 6.

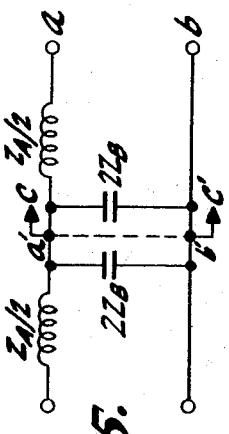


Fig. 5.

Fig. 7.

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TRANSMISSION LINE FILTER

The invention herein described was made in the course of or under a contract or subcontract thereunder with the Department of the Air Force.

This invention relates to transmission line filters.

The prior art discloses a wide variety of coaxial transmission line filters for filtering high frequency signal waves. In this area, much attention has been given to the development of low pass coaxial transmission line filters.

A general approach in designing coaxial filters has been to design a lumped element circuit in accordance with a desired frequency response and to build the equivalent distributed parameter circuit in coaxial form.

One of the early developments in the construction of low pass coaxial filters is shown in U.S. Pat. No. 2,438,913. This patent discloses a coaxial low pass filter which is the distributed equivalent of a lumped circuit comprising cascaded pi sections of inductors and capacitors. In the distributed system, shown therein, a series of quarter wavelength cylindrical conductors are used to provide the desired shunt capacitance. Interspersed between the solid cylindrical conductors are quarter wavelength sections of coaxial transmission line for providing relatively high impedance series inductance between the shunt capacitive sections.

The new result of the latter configuration is a filter comprising alternating sections of high and low impedance, each section being a quarter wavelength long at a desired frequency, to provide low pass filtering.

Another transmission line filter is shown in U.S. Pat. No. 2,700,136. Here again the filter is designed to be a coaxial low pass type filter. Instead of utilizing solid cylindrical elements to provide distributed shunt capacitance, this filter uses cup-like structures of equal lengths to provide distributed capacitance and to set up reflections within the filter in order to block frequencies above the desired low pass band.

Recent developments in the area of coaxial transmission line filters are summarized in an article in the I.E.E.E. Transactions on Microwave Theory and Techniques, September, 1965, pages 514–518. Here again a coaxial low pass filter is shown wherein a particular frequency response, such as a Tchebyscheff or Butterworth response, is desired.

The article shows solid cylindrical elements with equal lengths and varying diameters, equally spaced along an inner conductor.

All of the aforementioned approaches suffer the same disability by virtue of their construction. When the latter filters are operated at a frequency such that the cylindrical elements are substantially a half wavelength long, the frequency response exhibits a spurious pass band. A spurious pass band will occur whenever the electrical length of the cylindrical elements approaches any multiple of a half wavelength.

In narrow band applications the spurious pass bands present no significant problem. In broad band applications, however, or situations where the user is concerned with harmonics, these spurious pass bands represent a serious detriment to the performance of the filter.

The invention shown herein is a coaxial transmission line filter in which a plurality of open end equal diameter cylindrical conductors, having various predetermined lengths, are spaced along the inner conductor of the coaxial line. The cylindrical conductors have various predetermined spacings between each other. Furthermore, the open end cylindrical conductors are short circuited to the inner conductor. The arrangement of the cylindrical conductors and spacings therebetween provides a frequency response which substantially eliminates at least one spurious pass band in the frequency response characteristic of the filter.

IN THE DRAWINGS

FIG. 1 is a schematic diagram of the lumped parameter equivalent of the desired filter;

FIG. 2 is a sketch representing a prior art coaxial filter;

FIG. 3 is the frequency response curve associated with the prior art filter of FIG. 2;

FIG. 4 is an offset cut-away pictorial of a coaxial filter embodying the present invention;

FIG. 5 is a schematic diagram of a typical lumped circuit TEE section of FIG. 1;

FIG. 6 is a sketch of a typical distributed parameter T of FIG. 4; and

FIG. 7 is a curve showing the frequency response associated with the filter of FIG. 4.

The embodiment of the present invention is shown as a low pass filter; however, the invention is not limited to use in the field of low pass filters and may be used in conjunction with other desired frequency responses.

The circuit in FIG. 1 shows the typical arrangement of a lumped element low pass filter comprising a series of T sections. The diagram further shows a source load, R_g, of 50 ohms and a load impedance, R_L, of 50 ohms. The series inductance elements L_1, L_3, L_5, etc., and the shunt capacitance elements C_2, C_4, C_6, etc., are selected to provide a desired frequency response for the filter, such as the Tchebyscheff or Butterworth response. The element values for a particular response may be readily determined by reference to many standard textbooks containing appropriate tables of values corresponding to the desired response.

Referring now to FIG. 2, assume that the prior art filter shown is to be constructed as the equivalent of a lumped parameter circuit as shown in FIG. 1 wherein the element values have been appropriately selected to provide the desired frequency response. The cylindrical elements $\mathbf{20_2}$–$\mathbf{20_{n-1}}$ roughly correspond to the shunt capacitors, C_2, C_4, C_6, etc., shown in FIG. 1. The sections of transmission line $\mathbf{22_1}$–$\mathbf{22_n}$ roughly correspond to the series inductors, L_1, L_3, L_5, etc., shown in FIG. 1.

There are well-known expressions for determining the appropriate diameters of cylindrical elements $\mathbf{20_2}$–$\mathbf{20_{n-1}}$ and the diameters D_1 and D_2 of the coaxial transmission line to obtain the corresponding series inductance and shunt capacitance values of FIG. 1. The inductance per unit length of a coaxial transmission line is given by;

$$L = 0.4605\mu_1 \left(\log_{10} \frac{D_1}{D_2}\right) \times 10^{-8} \text{ henry/cm.} \quad (1)$$

Where μ_1 is the permeability of the medium separating the conductors, D_1 is the inner diameter of the outer conductor, and a D_2 is the outer diameter of the inner conductor.

The expression for the capacitance per unit length of a coaxial transmission line is given by:

$$C = \frac{0.241\epsilon_1}{\log_{10}\left(\frac{D_1}{D_2}\right)} \times 10^{-12} \text{ Farad/cm.} \quad (2)$$

Where ϵ_1 is the dielectric constant of the medium separating the conductors.

In the typical prior art filter both the predominantly capacitive section $\mathbf{20_2}$–$\mathbf{20_{n-1}}$ and the predominantly inductive sections $\mathbf{22_1}$–$\mathbf{22_n}$ are all of the same electrical length θ. The relative diameters shown in FIG. 2 may be adjusted either analytically or by trial and error, to compensate for fringing field effects.

FIG. 3 shows the resulting frequency response of the filter constructed as shown in FIG. 2. In the plot of attenuation versus frequency, the curve shows the relative location of the cut-off frequency, f_c, and the high attenuation frequency f_1. At the frequency f_1 the electrical lengths, θ, of the closed cylindrical elements $\mathbf{20_2}$–$\mathbf{20_{n-1}}$ of FIG. 2 are substantially a quarter wavelength.

FIG. 3 further shows the filter response when the element electrical length, θ, approaches a half wavelength at frequency f_2 It is the low attenuation area in the vicinity of frequency f_2 which is defined as the first spurious pass band region. Had the curve of FIG. 3 been extended in frequency range there would be other spurious pass band regions shown at frequencies where the electrical length, θ, becomes a multiple of a half wavelength.

Referring now to FIG. 4, an embodiment of the invention is shown in terms of a coaxial low pass filter having an outer conductor **39** and an inner coaxial conductor **40**. Outer conductor **39** has an inner diameter d_1. Inner conductor **40** has an outer diameter d_2. Open end cylindrical conductors **41–47**, having various lengths l_1–l_7 are coaxially disposed with respect to conductors **39** and **40**, and are spaced along inner conductor **40** at spacings s_1–s_8. Each of the conductors **41–47** are electrically short-circuited to the center conductor **40** by disc-like members **50**. At the edge of each open end of conductors **41–47** there is a corona ring **51** for purposes of high power breakdown protection. Dielectric spacers **52** are provided between the inner surface of the outer conductor **39** and cylindrical conductors **41–47** to insulate the cylinders **41–47** from conductor **39** and to maintain the spacings s_1–s_8 between cylinders **41–47**.

In order to arrive at the structure shown in FIG. **4**, the procedure is to start with a desired filter specification and frequency response. In the embodiment shown in FIG. **4**, 50 db of attenuation is required at the second harmonic of the lowest pass frequency. The cut-off frequency, f_c. for this particular filter is 428 mhz and the required band width is 46 percent.

The latter specifications can be met with a 15 element, 0.01 db ripple Tchebyscheff lumped parameter circuit low pass filter.

In order to determine the appropriate values for the inductors and capacitors of the desired lumped parameter circuit, standard Tchebyscheff distribution tables are consulted. Such a table may be found on page 102 of Microwave Filters, Impedance-Matching Networks, and Coupling Structures, by Matthaei, Young and Jones published by the McGraw-Hill Company.

The values in the aforementioned table are normalized to 1 ohm. In utilizing a 50 ohm source impedance and a 50 ohm load impedance the values given in the tables must be multiplied by 50. At the cut-off frequency of 428 mhz the following impedance values, in ohms, for the 15 elements, corresponding to the elements of the desired lumped parameter circuit shown in FIG. **1**, are obtained;

Z_1=+j.....	41.60	Z_6=−j....	27.364	Z_{11}=+j...	99.485
Z_2=−j.....	34.247	Z_7=+j....	101.08	Z_{12}=−j...	28.274
Z_3=+j.....	92.60	Z_8=−j....	27.183	Z_{13}=+j...	92.60
Z_4=−j.....	28.274	Z_9=+j....	101.08	Z_{14}=−j...	34.247
Z_5=+j.....	99.485	Z_{10}=−j...	27.364	Z_{15}=+j...	41.60

Having found the element values for the lumped parameter circuit, it is now necessary to determine the characteristic impedances for the high and low impedance sections of the distributed parameter filter.

Another form for the inductance and capacitance per unit length of a coaxial transmission line is given by;

$$L=\frac{Z_0}{v} \text{ and } C=\frac{1}{Z_0 v} \qquad (3, 4)$$

Where Z_0 equals the characteristic impedance of the line and v is the velocity of propagation in the line.

The object here is to maximize the characteristic impedance of the inductive sections of transmission line and minimize the characteristic impedance of the capacitive sections of cylindrical elements. With consideration given to current carrying capacity and higher order modes, the characteristic impedance of the predominantly inductive sections of transmission line is set at 150 ohms and the characteristic impedance of the predominantly capacitive cylindrical sections is set at 12 ohms. The selected values of the high and low characteristic impedances will vary according to the particular application.

Once the characteristic impedances have been determined, the diameters of the coaxial transmission line d_1, d_2 and the outer diameter D_1 of the cylindrical elements are determined (from Equations 1–4) by the following relationships;

$$12 \text{ ohms}=K \log\left(\frac{d_1}{D_1}\right) \text{ and } 150 \text{ ohms}=K \log\left(\frac{d_1}{d_2}\right) \qquad (5, 6)$$

Where

$$K=138\sqrt{\frac{\mu_1}{\epsilon_1}}$$

and where μ_1 is the permeability of the medium separating the conductors and ϵ_1 is the dielectric constant of the medium separating the conductors.

In the embodiment shown in FIG. **4**, $d_1=3.027$ inches, $d_2=0.25$ inches and the $D_1=2.50$ inches.

Having established the element values for the lumped parameter circuit and the relationship between the coaxial diameters of the distributed parameter filter, there remains the task of establishing the lengths l_1-l_7 of the cylindrical conductors **41–47**, of FIG. **4**, and the spacings s_1 – s_8 therebetween.

In FIG. **5** a typical general symmetrical lumped parameter T is shown with the impedance representing the shunt capacitance divided equally into two parallel capacitors with impedances of $2Z_B$. The impedance corresponding to the series inductance is given by $Z_A/2$.

By dividing up the shunt capacitance in the manner shown in FIG. **5**, the circuit is symmetrical about the dashed line C, C'. Rather than analyzing the entire T-section, one may now analyze one-half of the T.

Considering the circuit between terminals a,b and terminals a', b', the open circuit impedance looking into terminals a,b is given by:

$$Z_{o.c.}=\frac{Z_A}{2}+2Z_B \qquad (7)$$

Similarly, the short circuit impedance looking into terminals a,b is given by:

$$Z_{s.c.}=\frac{Z_A}{2} \qquad (8)$$

The procedure now is to look at a typical distributed parameter T-section as shown in FIG. **6**, and develop the short circuit and open circuit impedance equations looking into one-half of the typical distributed T-section. By equating the image parameters of the lumped circuit with the image parameters of the distributed T at the cutoff frequency, one obtains a direct equivalence between the lumped and distributed sections.

In the desired total filter circuit, corresponding to FIG. **1**, the values of series inductance and shunt capacitance previously obtained from the tables for each of the several T-sections shown have similarly been divided to provide the type of symmetry shown in FIG. **5**.

The distributed T of FIG. **6** represents any one of the cylindrical sections **41–47** and associated lengths of transmission line shown in FIG. **4**. The generalized T is also divided about the line E, E'. By taking one-half of the distributed T-section, the parameters for the cylindrical section may be determined by analyzing one-half of the total section.

The approach with respect to FIG. **6** is to develop the open circuit and short circuit image parameters of the input impedance Z_3, in order to match the image parameters of the distributed T with the lumped circuit T at the cutoff frequency.

The one-half T-section of the cylinder **70** in FIG. **6** comprises the parallel combination of a transmission line of length L_{11}, with a characteristic impedance of Z_{01}, and the fringing field capacitance C_x. The impedance of the parallel combination is termed Z_1 and is given by the equation;

$$Z_1=j\frac{Z_{01}\tan BL_{11}}{1-\omega C_x Z_{01}\tan BL_{11}} \qquad (9)$$

Where ω is the frequency in radians per second, and B is the phase constant of the coaxial line.

The input impedance Z_3 is further comprised of the impedance Z_2 which is the parallel combination of (i) a transmission line having a length L_{22}, with a characteristic impedance

Z_{02}, and (ii) shunt capacitance C_y. The characteristic impedance of Z_{02} represents the characteristic impedance of the coaxial transmission line wherein cylinder **70** corresponds to the inner conductor and conductor **39** remains, as before, the outer conductor.

In FIG. **6** it is shown that the length L_{11} is related to the length L_{22} by a constant. The incremental difference between L_{22} and L_{11} is one-half the thickness of the short circuiting disk **50**. The impedance Z_2 has a short circuit and an open circuit equation associated with it. The open circuit representation of Z_2 is given by;

$$Z_{2o.c.}=-j\frac{Z_{02}\cot BL_{22}}{1+\omega C_y Z_{02}\cot BL_{22}} \quad (10)$$

The short circuit representation of the impedance Z_2 is given by;

$$Z_{2s.c.}=j\frac{Z_{02}\tan BL_{22}}{1-\omega C_y Z_{02}\tan BL_{22}} \quad (11)$$

The input impedance Z_3 looking into the distributed one half T-section of FIG. **6** is further comprised of a length of transmission line having a characteristic impedance of Z_{03} and a length of L_{33}.

The resulting expression for the total input impedance Z_3 is given by;

$$Z_3=Z_{03}\frac{(Z_1+Z_2)+jZ_{03}\tan BL_{33}}{Z_{03}+j(Z_1+Z_2)\tan BL_{33}} \quad (12)$$

The input impedance Z_3 under open circuit conditions is given by;

$$Z_{3o.c.}=Z_{03}\frac{(Z_1+Z_{2o.c.})+jZ_{03}\tan BL_{33}}{Z_{03}+j(Z_1+Z_{2o.c.})\tan BL_{33}} \quad (13)$$

The input impedance Z_3 under short circuit conditions is given by;

$$Z_{3s.c.}=Z_{03}\frac{(Z_1+Z_{2s.c.})+jZ_{03}\tan BL_{33}}{Z_{03}+j(Z_1+Z_{2s.c.})\tan BL_{33}} \quad (14)$$

The values for the capacitance C_x and C_y are measured experimentally. As previously noted the lengths L_{11} and L_{22} are related by a constant. Therefore it is only the lengths L_{33} and L_{22} or L_{11} which must be determined.

The open circuit and short circuit input impedance for the distributed TEE $Z_{3\,o.c.}$ and $Z_{3\,s.c.}$ is now equated to the open circuit and short circuit input impedance of the lumped circuit T $Z_{o.c.}$ and $Z_{s.c.}$. The result is two equations having two unknowns.

$$Z_{o.c.}=Z_{3\,o.c.} \quad (15)$$

$$Z_{s.c.}=Z_{3\,s.c.} \quad (16)$$

Solving equations 15 and 16 for the lengths L_{33} and L_{11} or L_{22} at the cutoff frequency provides a direct equivalence between the lumped circuit symmetrical TEE and the distributed circuit T.

Carrying out the above processes for each half cylinder of cylinders **41–47** of FIG. **4**, the following results, in inches, for the embodiment shown are obtained;

s_1=0.751	s_5=1.514
s_2=1.558	s_6=1.518
s_3=1.518	s_7=1.558
s_4=1.514	s_8=0.751
l_1=0.926	l_5=1.382
l_2=1.320	l_6=1.320
l_3=1.382	l_7=0.926
l_4=1.414	

The filter of FIG. **4** is now fully defined with respect to the appropriate lengths $l_1 - l_7$ and the spaces $s_1 - s_8$ between cylinders **41–47**.

The resulting frequency response of the embodiment of the filter of FIG. **4** is shown in FIG. **7**. The frequency f_2 is the frequency about which the spurious pass band would ordinarily be centered had a prior art approach been used. As shown in FIG. **7**, the frequency response exhibits a dip at frequency f_2 but does not pass signals as shown in the corresponding frequency response curve of FIG. **3**. In actual use of the embodiment herein described, attenuation levels of greater than 50 db at f_2 have been achieved.

The frequency f_2 is that frequency at which the average length of cylinders **41–47** is approximately one half wavelength long. That is, the frequency where the sum of the lengths, $l_1+l_2+l_3\ldots+l_7$ divided by the number of cylinders, i.e., seven, is equal to roughly a half wavelength. The mechanism here involved is thought to be that while the average length of the cylinders **41–47** approach a half wavelength, the average length of the half sections or cup-like structures approaches a quarter wavelength, thereby tending to decouple the associated cylindrical conductors from the line.

Furthermore, the staggered lengths of the cylinders tend to spread out the range of frequencies for which at least one section will have a cup-like element which presents a very high series impedance to decouple or impede the pass band tendency. In addition, the symmetry between the left and right halves of the disclosed filter causes equal reflections from each half to alternatively fall in and out of phase as the frequency is scanned. At the frequencies where the reflections from each half tend to cancel each other, the ratio of circulating to real power is kept very high by the cup-like sections thereby causing a significant attenuation to be maintained at those frequencies where the internal reflections would otherwise cancel.

Although the invention described herein is given in the embodiment of a low pass coaxial transmission line filter, it is evident that the invention may be utilized in coaxial filters having other desired frequency responses.

What is claimed is:

1. In a coaxial transmission line low pass filter of the type having an outer conductor and a coaxial inner conductor, said filter having a plurality of cylindrical conductors coaxial with and spaced along said inner conductor, the diameter of each of said cylindrical conductors being greater than the outer diameter of said inner conductor and less than the inner diameter of said outer conductor, said cylindrical conductors cooperating with said outer conductor to provide distributed capacitance sections of relatively low characteristic impedance and wherein lengths of transmission line comprising portions of said inner and outer conductors extending between adjacent cylindrical conductors provide distributed inductance sections of relatively high characteristic impedance, the improvement wherein:

said cylindrical conductors are open at each end thereof, said cylindrical conductors being of equal given diameter and wherein means, centrally located within said cylindrical conductors, are provided for electrically short circuiting each of said cylindrical conductors to said inner conductor, adjacent cylindrical conductors having various different predetermined lengths and various longitudinal predetermined spacings therebetween along said inner conductor, said predetermined cylindrical conductor lengths being determined such that the average length of said cylindrical conductors is substantially a half wavelength at a given frequency wherein the average length of the corresponding portion of said cylinders between said centrally located short circuiting means and one end of said cylinder is substantially a quarter wavelength long at said given frequency for providing substantial elimination of at least one spurious pass band in the frequency response of said filter.

2. A transmission line filter having a substantially low pass frequency response comprising:

an inner conductor having an outer diameter;

an outer conductor, coaxial with said inner conductor, having an inner diameter larger than said outer diameter;

a plurality of open end equal diameter cylindrical conductors positioned along said inner conductor and coaxial

with said inner and outer conductors, said cylindrical conductor diameter being greater than said outer diameter and less than said inner diameter, adjacent cylindrical conductors having various different predetermined lengths and having various predetermined spacings longitudinally along said inner conductor, each of said cylindrical conductors being electrically short circuited to said inner conductor by a disc-like conducting member centrally located within each of said cylindrical conductors, said disc-like members forming two symmetrical cup-like structures within each of said cylindrical conductors, and wherein said predetermined cylindrical conductor lengths are determined such that the average length of said cylindrical conductors is substantially a half wavelength at a given frequency whereas the average length of the corresponding cup-like structures is substantially a quarter wavelength long at said given frequency causing relatively high attenuation at said given frequency, thereby substantially eliminating at least one spurious pass band in the frequency response of said filter.

3. The filter according to claim 2 wherein there is attached at each of said open ends of said cylindrical conductors a conductive corona ring.

4. The filter according to claim 2 wherein there are a plurality of cylindrical conductors having symmetry with respect to spacings and lengths about a centrally located plane normal to said inner conductor.

5. The filter according to claim 2 wherein a dielectric material is located on the inner surface of said outer conductor for insulating said cylindrical conductors from said outer conductor and for supporting said cylindrical conductors.

* * * * *