Sept. 2, 1947. W. P. MASON 2,426,633

WAVE TRANSMISSION NETWORK

Filed Aug. 12, 1943

FIG. 1

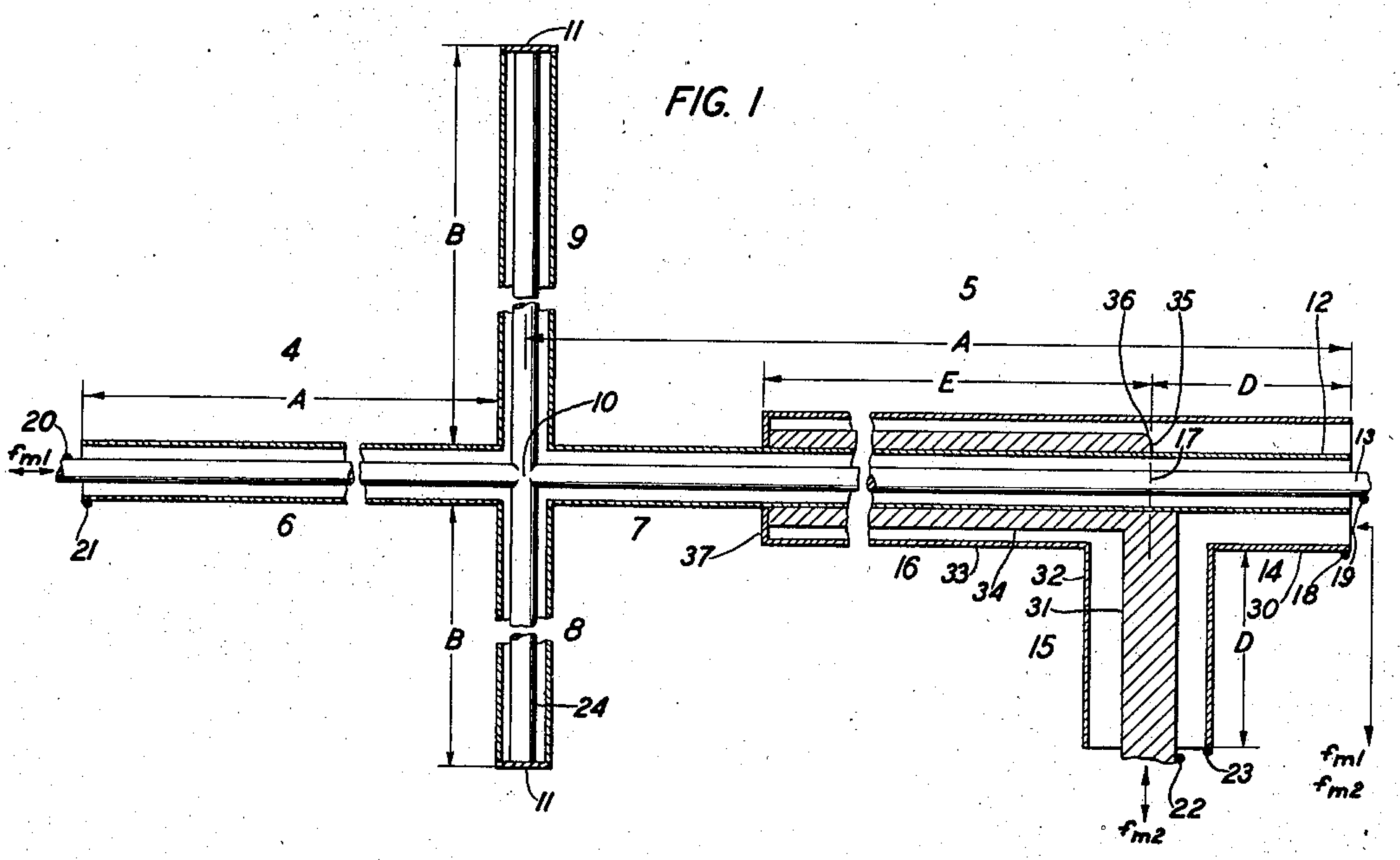


FIG. 2

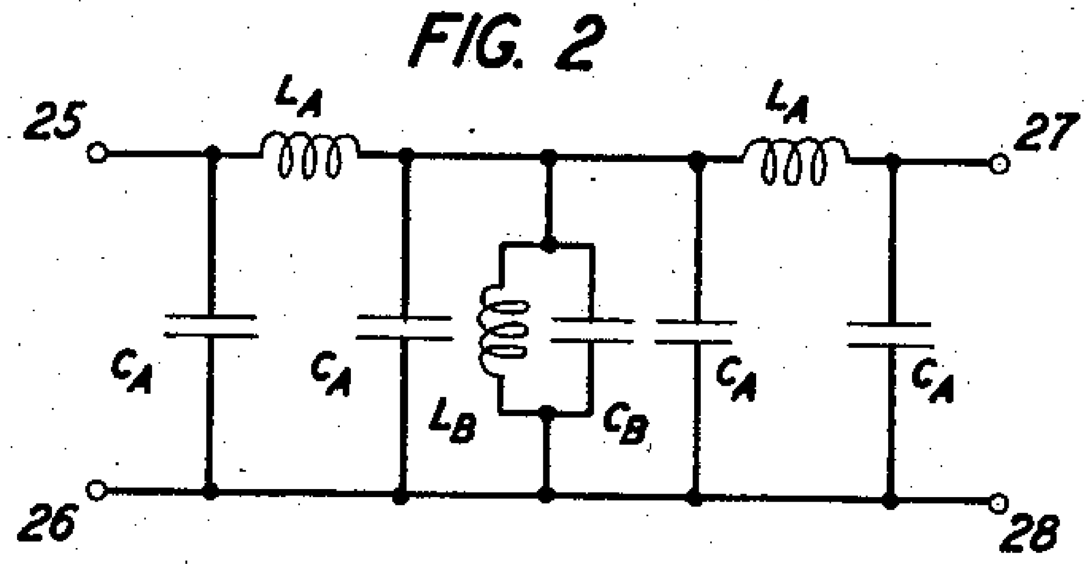


FIG. 3

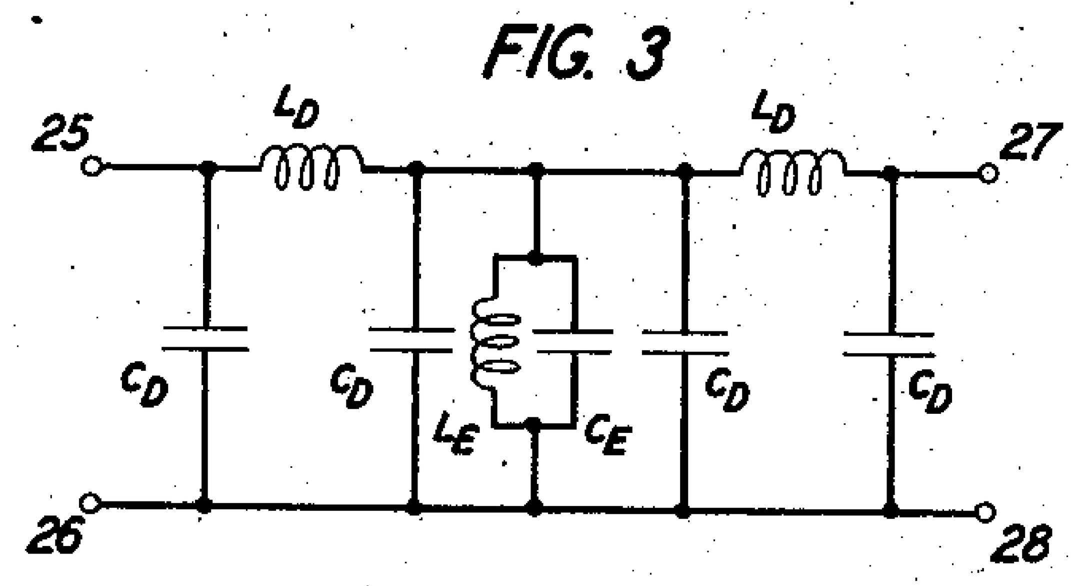
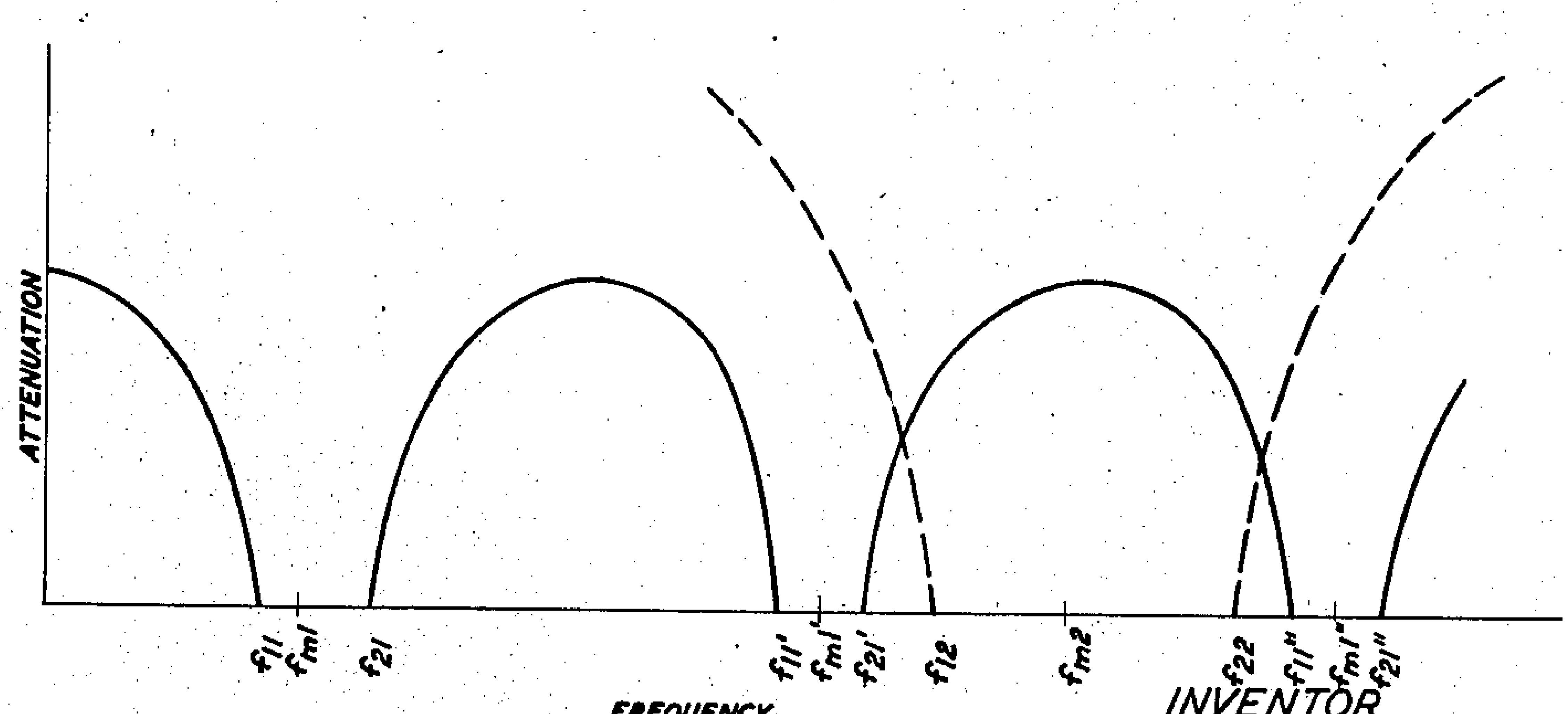


FIG. 4



INVENTOR
W. P. MASON

BY

Ralph T. Holcomb

ATTORNEY

Patented Sept. 2, 1947

2,426,633

UNITED STATES PATENT OFFICE

2,426,633

WAVE TRANSMISSION NETWORK

Warren P. Mason, West Orange, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application August 12, 1943, Serial No. 498,325

11 Claims. (Cl. 178—44)

1

This invention relates to wave transmission networks and more particularly to branching circuits comprising a plurality of series-connected wave filters made up of sections of coaxial transmission line for combining or separating a plurality of different bands of frequencies.

The principal object of the invention is to place upon a common transmission line simultaneously a plurality of bands of frequencies from different sources or to separate into individual channels a plurality of bands simultaneously transmitted by one line.

Another object is to increase the voltage rating of filters comprising coaxial elements.

Other objects of the invention are to reduce the size and cost and increase the shielding of a series-connected branching circuit.

A branching circuit is required whenever two or more bands of frequencies from different sources are to be put on one transmission line or when signals on a line are to be separated into individual channels according to frequency. In accordance with the invention the channels of such a branching circuit are connected in series. Each channel is provided with a band-pass filter comprising two sections of coaxial transmission line connected in tandem and one or more sections connected in shunt at their junction. In order to provide a fully shielded compact structure all of the series branches at the connected ends of the filters are arranged concentrically. With this construction the inner conductor of one branch serves as the outer conductor of another branch. In each of the filters except the one of lowest frequency there is a short-circuited coaxial shunt branch which is arranged in line with the concentric series branch and the other series branch makes a right angle with the concentric series branch. The voltage rating of any of the filters may be increased economically by providing a plurality of coaxial shunt branches of the same length connected in parallel at the same point, thus increasing the separation between the inner and the outer conductors. Also, to simplify the construction, all of the coaxial elements of any one filter may be made with outer conductors of the same inner diameter.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawings in which like reference characters refer to similar or corresponding parts, and in which:

Fig. 1 is a longitudinal cross-section of a two-channel branching circuit in accordance with the invention;

2

Figs. 2 and 3 show the equivalent electrical circuits for the filters used in the arrangement of Fig. 1; and

Fig. 4 gives typical attenuation-frequency characteristics for the filters.

Fig. 1 shows two band-pass wave filters 4 and 5 connected in series at one end to form a two-channel branching circuit. Each of the filters 4 and 5 is a ladder structure composed of sections of coaxial transmission line. The filter 4 comprises two similar tandem-connected sections of line 6 and 7, each of length A, and two identical sections 8 and 9, each of length B, short-circuited at their distant ends by end plates 11 and connected in shunt at the junction point 10 of the sections 6 and 7. The section 7, for example, consists of an outer cylindrical conductor 12 and coaxial therewith an inner conductor 13. The filter 5 comprises two tandem-connected sections of line 14 and 15, each of length D, and a single shunt section 16 of length E connected at the junction point 17 and short-circuited at its distant end by the annular plate 37. The sections 14 and 16 are arranged in axial alignment and are concentric with the line section 7 of the filter 4. The outer conductor 12 of the section 7 thus serves as the inner conductor of the sections 14 and 16. The axis of the section 15 makes a right angle with the axis of the sections 14 and 16. With this construction both mounting space and material are conserved and continuous shielding is provided for the entire branching circuit. In order to save drawing space, in Fig. 1 portions of the line sections 6, 7, 8, 9 and 16 have been removed.

The filter 4 is designed to transmit a band with mid-band frequency of f_{m1} and the filter 5 a higher band with mid-band frequency f_{m2}. Since the filters are connected in series at their right-hand ends, if signals falling within these bands are impressed upon the circuit at the terminals 18, 19, the lower frequency signals may be taken off at the terminals 20, 21 and the higher frequency signals at the terminals 22, 23 for utilization in separate channels. Alternatively, signals within these bands from separate sources may be impressed upon the terminals 20, 21 and 22, 23 respectively, and combined in a utilization circuit connected to the terminals 18, 19. These possibilities are indicated by the double pointed arrows and the appropriate mid-band frequencies associated therewith.

The electrical design of the filters will now be considered. It will be assumed that the filter 4 is required to transmit a band of frequencies extending from f_{11} to f_{21} with a mid-band frequency of f_{m1}, which is the geometric mean of the two, and the filter 5 a higher band between f_{12} and f_{22} with a mid-band frequency of f_{m2}. The design may be worked out most conveniently by referring to the equivalent electrical circuit which for the filter 4 is shown in Fig. 2. The circuit is a ladder-type network with input terminals 25, 26 and output terminals 27, 28. The series inductance L_A at the left and the two capacitances C_A, C_A connected in shunt at the ends thereof are furnished by the line section 6. The series inductance L_A at the right and the two shunt capacitances associated therewith are supplied by the line section 7. The central shunt branch made up of the inductance L_B and the capacitance C_B connected in parallel represents the two shunt-connected line sections 8 and 9.

The approximate values of these elements in terms of the lengths and characteristic impedances of the line sections are given by the following formulas:

$$C_A=\frac{A}{2VZ_A}\text{ farads} \qquad (1)$$

$$L_A=\frac{AZ_A}{V}\text{ henries} \qquad (2)$$

$$C_B=\frac{nB}{2VZ_B}\text{ farads} \qquad (3)$$

$$L_B=\frac{8}{\pi^2}\frac{BZ_B}{nV}\text{ henries} \qquad (4)$$

in which A and B are the lengths in centimeters of the line sections 6 and 8 respectively, Z_A and Z_B are respectively their characteristic impedances, n is the number of identical shunt branches and V is the velocity of propagation in the sections, which may be taken as 3×10^{10} centimeters per second. It is assumed that the series resistance and distributed conductance of the line sections are small enough to be neglected. In Equation 4 the factor $8/\pi^2$ is used because the length of section 8 is in the neighborhood of a quarter wavelength and is short-circuited at the end. In this connection reference is made to Equation 2.139 and the accompanying discussion on page 65 of applicant's book, "Electromechanical Transducers and Wave Filters," published by D. Van Nostrand, Inc.

The two capacitances C_A, C_A connected in shunt at the ends of the circuit of Fig. 2 are usually small enough to be neglected. When this is done, the remaining circuit will be recognized as a mid-series terminated filter section of the type shown as structure 12 in Table I on pages 52 and 53 of applicant's above-mentioned book, the design formulas for which, as applied to Fig. 2, are as follows:

$$L_A=\frac{Z_0}{2\pi f_{21}} \qquad (5)$$

$$L_B=\frac{Z_0(f_{21}^2-f_{11}^2)}{4\pi f_{11}^2 f_{21}} \qquad (6)$$

$$2C_A+C_B=\frac{f_{21}}{\pi Z_0(f_{21}^2-f_{11}^2)} \qquad (7)$$

where Z_0 is the image impedance of the filter at the mid-band frequency f_{m1}.

A suggested design procedure for the filter 4 will now be presented. The image impedance Z_0 is usually chosen to match the impedance of the loads which are to be connected to the terminals 18, 19 and 20, 21. The cut-off frequencies f_{11} and f_{21} are chosen and the required values of the elements L_A, L_B and the sum of $2C_A$ and C_B are computed from Equations 5, 6 and 7. The length B of each of the shunt branches 8 and 9 is next chosen. This may conveniently be taken as a quarter wavelength at the mid-band frequency in accordance with the formula:

$$B=\frac{V}{4f_{m1}} \qquad (8)$$

The number n of shunt branches that will be required is ordinarily not known at this stage so it may be taken as unity. The impedance Z_B of a single shunt branch as thus determined may be multiplied by n to find the impedance of each shunt branch as explained more fully below. Now the value of L_B found from Equation 6 and the length B as given by Equation 8 are substituted in Equation 4 to find the characteristic impedance Z_B of the shunt branch, assuming that n is unity. Next the value of C_B is found from Equation 3. Since the sum of $2C_A$ and C_B is known from Equation 7, the value of C_A can be found. This value of C_A is substituted in Equation 1, the value of L_A as found from Equation 5 is substituted in Equation 2 and the two equations solved simultaneously for the required length A and characteristic impedance Z_A of each series branch 6 and 7. In a coaxial line the ratio of the inner diameter b of the outer conductor to the diameter a of the inner conductor is related to the characteristic impedance Z_K of the line by the formula:

$$Z_K=60\log_\epsilon\frac{b}{a} \qquad (9)$$

The number n of shunt branches required depends primarily upon the peak voltage that will be impressed upon the filter. As an illustrative example, if the filter 4 has an image impedance Z_0 of 50 ohms and is to transmit a band lying between 200 and 280 megacycles per second each of the branches 6 and 7 will have a length A of 18.42 centimeters and a characteristic impedance Z_A of 46.4 ohms and a single shunt branch will have a length B of 31.7 centimeters and a characteristic impedance of 15.96 ohms. The outer conductors of the series branches 6 and 7 and the shunt branch may most conveniently have the same inner diameter which should not be too large since the higher frequency filter 5 is to be built around the branch 7. Brass tubing having an outer diameter of half an inch or 1.270 centimeters, and an inside diameter of 1.107 centimeters is suitable. From Equation 9 the ratio of the inner diameter of the outer conductor to the diameter of the inner conductor for the single shunt branch will be 1,307, giving a diameter of 0.847 centimeter for the inner conductor. The outer and inner conductors will then have a separation of 0.130 centimeter.

It will be assumed that the peak voltage for the filter is 2,000 volts and that the allowable voltage gradient between inner and outer conductors of the coaxial elements is 10,000 volts per centimeter. It is apparent that the single shunt branch with a separation of 0.130 centimeter will withstand only 1,300 volts. However, in accordance with the invention, this situation may be remedied by increasing the number of shunt branches to n and making the characteristic impedance of each n times the impedance of the single shunt. The length of each of the n branches will be the same as that of the single shunt branch. As shown in Fig. 1, for example, two shunt branches 8 and 9 are used. The characteristic impedance of each will be two times 15.96 or 31.92 ohms. The ratio of diameters will be 1.702, giving a diameter of 0.649 for the inner conductor 24 and a separation of 0.229 centimeter. Each shunt branch will withstand a voltage of 2,290 volts, which is greater than the assumed peak voltage of 2,000 for the filter. The number of shunt branches may, of course, be increased to more than two, as, for example, to three or four, thus further increasing the voltage rating of the branches. Each of the series branches 6 and 7 will have a ratio of diameters of 2.75, giving a diameter of 0.509 centimeter for the inner conductor and a separation of 0.299 centimeter, which is more than adequate for a voltage of 2,000.

The solid line curve of Fig. 4 gives the attenuation-frequency characteristic of the filter 4. The filter has a multiband characteristic with the mid-band frequencies occurring at $(2s-1)\ f_{m1}$, where s is an integer. Only the first three transmission bands with mid-band frequencies of f_{m1}, f_{m1}' and f_{m1}'' are shown. All of these bands have the same width in cycles. It should be pointed out that any one of these bands may be utilized, either the first extending from f_{11} to f_{21}, the second from f_{11}' to f_{21}', the third from f_{11}'' to f_{21}'' or a higher one, depending upon the frequency range to be carried by the channel connected to the terminals 20, 21.

The electrical design of the filter 5 will now be considered. Fig. 3 gives the equivalent electrical circuit, which is similar to that of the filter 4 given in Fig. 2. The series inductances L_D, L_D, and their associated shunt capacitances C_D, are furnished respectively by the line sections 14 and 15. The shunt branch made up of L_E and C_E connected in parallel represents the line section 16.

The approximate values of these elements in terms of the lengths and characteristic impedances of the line sections are given by the following formulas:

$$C_D=\frac{D}{2VZ_D} \tag{10}$$

$$L_D=\frac{DZ_D}{V} \tag{11}$$

$$C_E=\frac{E}{2VZ_E} \tag{12}$$

$$L_E=\frac{8}{\pi^2}\ \frac{EZ_E}{V} \tag{13}$$

in which D and E are the lengths in centimeters of the line sections 14 and 16 respectively, and Z_D and Z_E are, respectively, their characteristic impedances. In the filter 5 it has been assumed that the voltage requirement can be met with a single shunt line section 16. However, if greater spacing between inner and outer conductors is required, two or more parallel-connected shunt branches may be used, as in the filter 4, in which case Equations 12 and 13 will be modified by the inclusion of the factor n as in Equations 3 and 4.

Neglecting the end shunt capacitances C_D, C_D, as was done in connection with the circuit of Fig. 2, the design formulas for the circuit of Fig. 3 are as follows:

$$L_D=\frac{Z_0}{2\pi f_{22}} \tag{14}$$

$$L_E=\frac{Z_0(f_{22}^2-f_{12}^2)}{4\pi f_{12}^2 f_{22}} \tag{15}$$

$$2C_D+C_E=\frac{f_{22}}{\pi Z_0(f_{22}^2-f_{12}^2)} \tag{16}$$

The first transmission band of the filter 5 is used and it is located within one of the attenuation bands of the filter 4. Preferably the third attenuation band is chosen, that is, the one between the upper cut-off f_{21}' of the second transmission band and the lower cut-off f_{11}'' of the third transmission band. If the second attenuation band, between the frequencies f_{21} and f_{11}', is chosen the sum of the lengths D and E may exceed A, resulting in an inconvenient mechanical structure.

The lower cut-off f_{12} of the filter 5 is, therefore, placed at a frequency interval above f_{21}' and the upper cut-off f_{22} at an interval below f_{11}''. These intervals are preferably approximately equal and each should be at least as large as half of the band width $f_{21}-f_{11}$ of the filter 4 to insure that the filter 4 will have a low enough image impedance over the band of the filter 5 for successful operation of the two filters in series. In the example shown the cut-offs f_{12} and f_{22} are located respectively, at the frequencies 805 and 1087 megacycles, giving a midband frequency of 935 megacycles. Since the third attenuation band of the filter 4 extends between 751 and 1142 megacycles, f_{12} is 54 megacycles above f_{21}' and f_{22} is 55 megacycles below f_{11}''. These intervals are larger than half of the 80 megacycle band width of the filter 4. The broken line curve of Fig. 4 shows the characteristic of the filter 5.

Using Equations 8 to 16 and the same design procedure outlined above in connection with the filter 4, each of the series line sections 14 and 15 of the filter 5 of the example will have a length D of 4.72 centimeters and a characteristic impedance of 46.6 ohms and the shunt line section 16 a length E of 8.02 centimeters and a characteristic impedance of 13.94 ohms. From Equation 9, it is found that for the series branches 14 and 15 the ratio of the inner diameter of the outer conductor to the diameter of the inner conductor will be 2.17 and for the shunt branch 16 this ratio will be 1.262. Since the conductor 12 with an outer diameter of 1.270 centimeters is the inner conductor of line section 14, the outer conductor 30 will have an inside diameter of 2.75 centimeters. The other series line section 15 will also have an inner conductor 31 with a diameter of 1.270 centimeters and an outer conductor 32 with an inner diameter of 2.75 centimeters. The diameter of the outer conductor 33 of the shunt line section 16 may conveniently be made the same as that of the series section 14, giving a diameter of 2.18 centimeters for the inner conductor 34. The required diameter for the inner conductor 34 may be provided by building up the outer diameter of the conductor 12 by adding material. Or, if desired, the inner conductor 34 may be in the form of a hollow cylinder with an annular plate at the end 35 which fits over the conductor 12. In order to prevent the formation of a corona discharge it is well to round off the end of the inner conductor 34 as shown at

36. In the line sections 14 and 15 the inner and outer conductors will have a separation of 0.74 and in the line section 16 a separation of 0.28, more than sufficient to withstand the peak voltage assumed.

The formulas involving the lengths of the coaxial line sections given herein are based upon the assumption that the concentric outer conductor will extend for the full length of the section. As is apparent in Fig. 1, however, when one branch, such as 15, is connected at a right angle to another branch, such as 14, at least a portion of the outer wall will be missing at the connected ends of the sections. In order to compensate for this condition the lengths of the line sections may have to be increased somewhat. This factor is of more importance in filters operating at the higher frequencies. In the case of side branches such as 8, 9 and 15 it has been found that a more nearly correct result will be obtained if the length is measured from the outer conductor, as shown by the dimensions B and D.

What is claimed is:

1. In combination, two wave filters connected in series at one end, each of said filters including a section of transmission line of the type comprising a cylindrical outer conductor and an inner conductor coaxial therewith, and the inner conductor of one of said sections serving also as the outer conductor of the other of said sections.

2. The combination in accordance with claim 1 in which said sections are located at the series-connected ends of said filters.

3. The combination in accordance with claim 1 in which one of said filters includes a second section of coaxial transmission line, said second section being arranged in axial alignment with said first-mentioned section in said one filter, and concentrically with respect to said section in said other filter.

4. The combination in accordance with claim 1 in which one of said filters includes two additional sections of coaxial transmission line of equal length connected in parallel with each other at the same point in said one filter.

5. The combination in accordance with claim 1 in which one of said filters includes a second section of coaxial transmission line, said second section being arranged in axial alignment with said first-mentioned section in said one filter and concentrically with respect to said section in said other filter and being short-circuited at one end.

6. The combination in accordance with claim 1 in which one of said filters includes a second section and a third section of coaxial transmission line, said second section being arranged in axial alignment with said first-mentioned section in said one filter and concentrically with respect to said section in the other of said filters and said third section being connected at the junction of said first-mentioned section and said second section in said one filter.

7. In combination, two wave filters connected in series at one end, each of said filters including a plurality of sections of coaxial transmission line, two of said sections in one of said filters being arranged in axial alignment with each other concentrically about one of said sections in the other of said filters, and one of said two sections in said one filter being short-circuited at one end.

8. The combination in accordance with claim 7 in which one of said filters includes two sections of coaxial transmission line of equal length connected in parallel with each other at the same point.

9. The combination in accordance with claim 7 in which one of said filters includes two sections of coaxial transmission line of equal length and the same characteristic impedance connected in parallel with each other at the same point.

10. The combination in accordance with claim 7 in which said one filter includes a third section of coaxial transmission line connected at the junction of said two sections in said one filter.

11. The combination in accordance with claim 7 in which said one filter includes a third section of coaxial transmission line connected at a right angle at the junction of said two sections in said one filter.

WARREN P. MASON.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
2,220,922	Trevor	Nov. 12, 1940
2,229,078	Hansell	Jan. 21, 1941
2,288,030	Salinger	June 30, 1942
2,241,616	Roosenstein	May 13, 1941
2,270,416	Cork et al.	Jan. 20, 1942
2,249,963	Lindenblad	July 22, 1941
2,284,529	Mason	May 26, 1942