

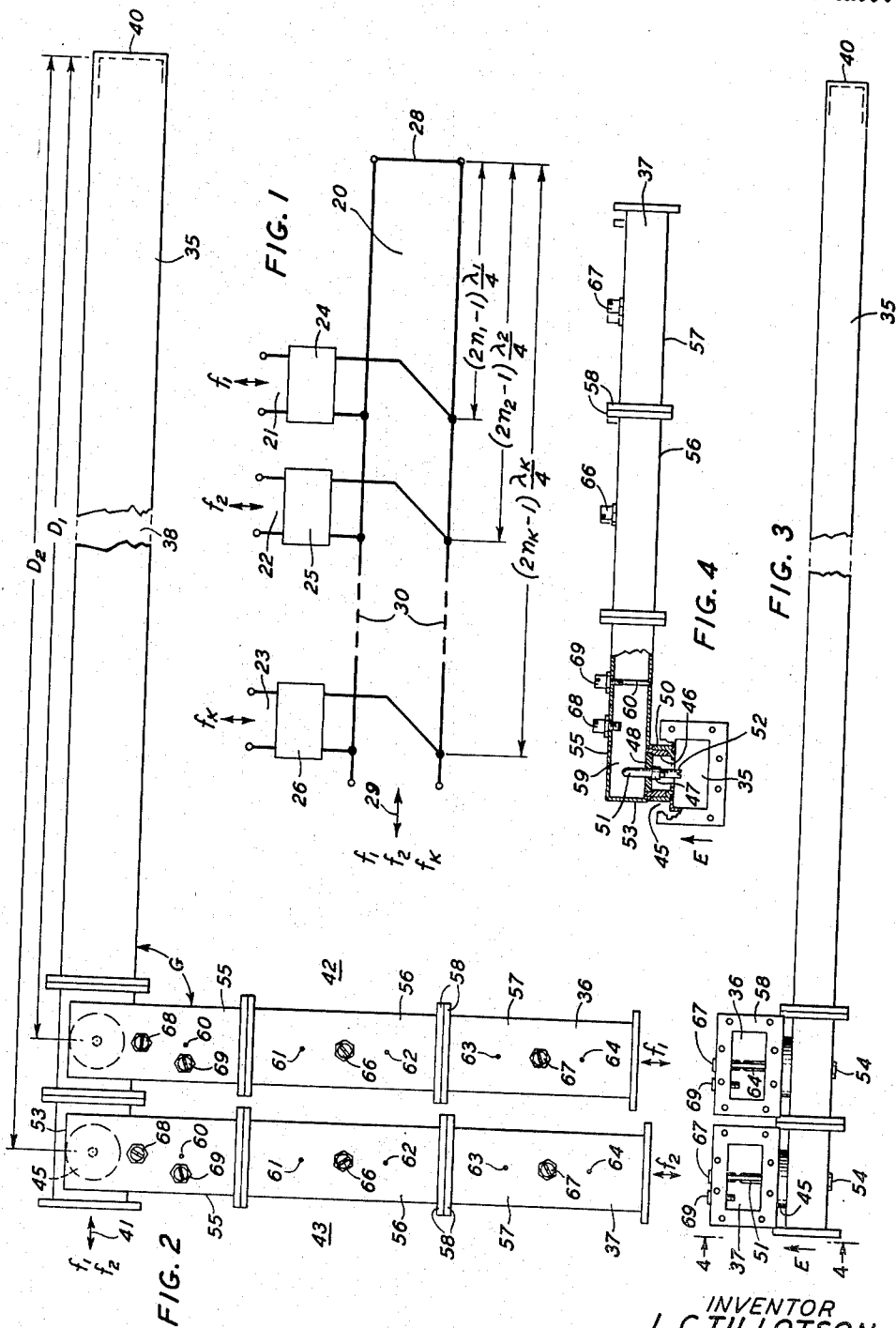
Aug. 17, 1954

LE ROY C. TILLOTSON
MICROWAVE BRANCHING ARRANGEMENT

2,686,902

Filed July 24, 1950

3 Sheets-Sheet 1



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FIG. 5

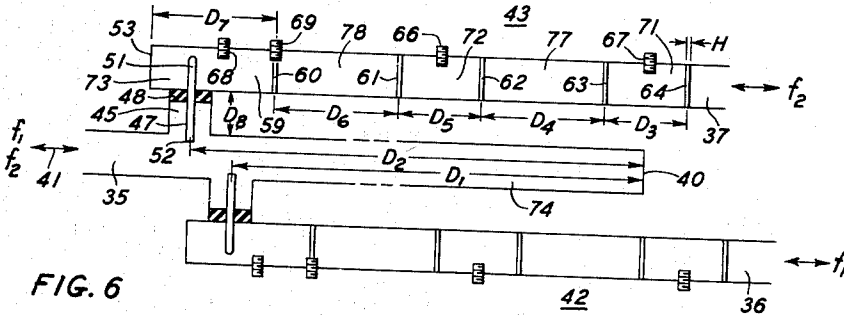


FIG. 6

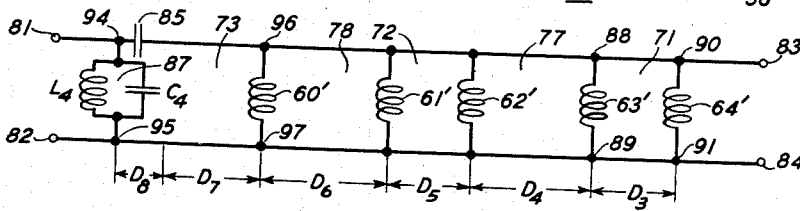


FIG. 14

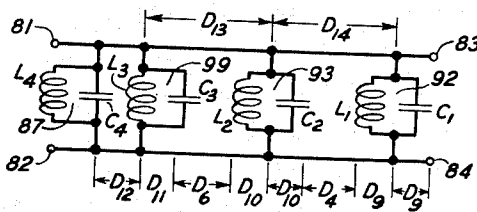


FIG. 7

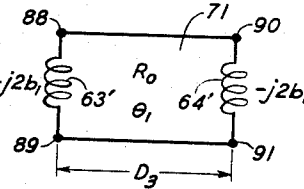


FIG. 16

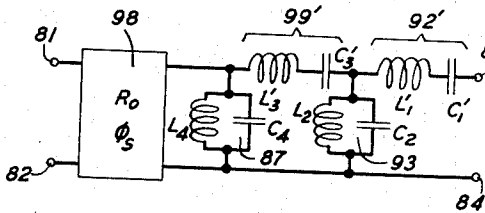


FIG. 8

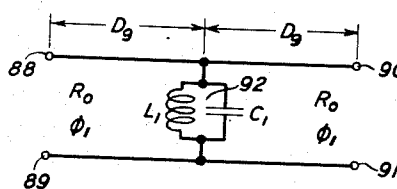


FIG. 9

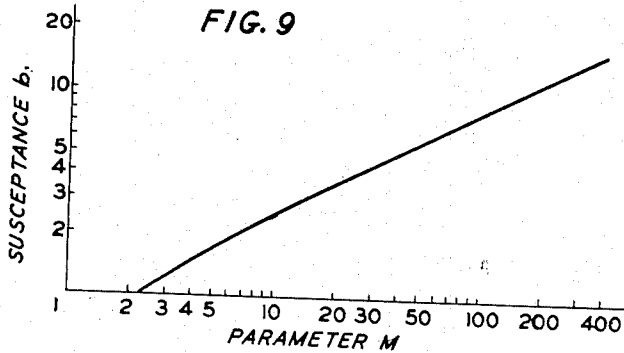
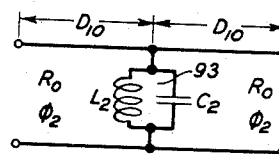


FIG. 11



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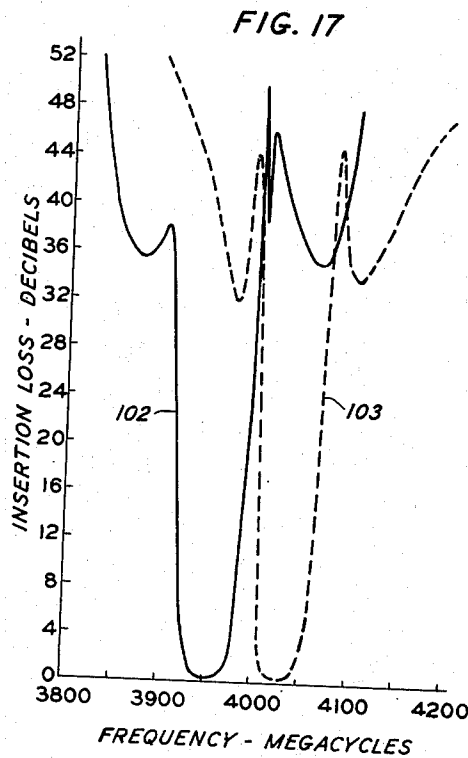
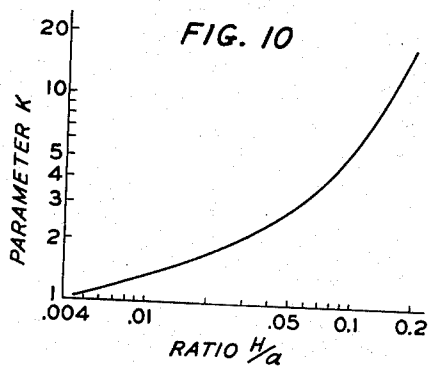
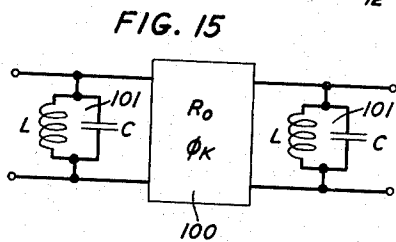
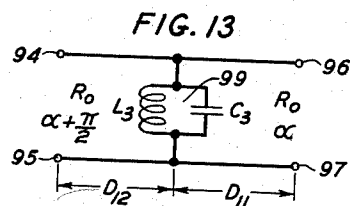
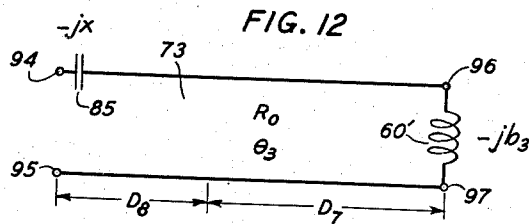
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UNITED STATES PATENT OFFICE

2,686,902

MICROWAVE BRANCHING ARRANGEMENT

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Application July 24, 1950, Serial No. 175,530

30 Claims. (Cl. 333-73)

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This invention relates to the transmission of guided electromagnetic waves and more particularly to a microwave branching arrangement.

The principal object of the invention is to separate guided electromagnetic waves into individual channels on a frequency basis or to introduce a plurality of different frequency bands into a single wave guide.

Another object is to minimize interaction between the different channels of such a branching arrangement.

A further object is to absorb or eliminate the disturbing effect of changes in the phase shift of the connecting lines between the channels.

Another object is to compensate for excess phase shift in the cavity resonators of the channel filters.

A further object is to compensate for the stiffness of sections of transmission line connecting the cavity resonators.

Other objects of the invention are to increase the mechanical and electrical flexibility of the system.

In one embodiment of the branching arrangement in accordance with the present invention a plurality of microwave filters having different mid-band frequencies are connected effectively in parallel at different points along a main wave guide which is closed at one end. Each filter is made up of a number of cavity resonators tuned to the mid-band frequency and connected by short sections of transmission line to form an equivalent ladder-type structure. The portion of the main guide between its closed end and the point of connection of a filter constitutes the first resonator. This portion has a length approximately equal to an odd integral number of quarter wavelengths at the mid-band frequency of the associated filter, thus making it antiresonant at that frequency, and a length so chosen that the resonator has approximately the stiffness called for by the filter design.

Each filter also comprises a section of wave guide which is closed at one end and contains a shunt reactor forming an end chamber therein. This chamber is connected to the main guide through a coaxial transmission line which cooperates with the chamber to form the second resonator of the filter. The coaxial line is coupled at one end through a series reactor to the main guide and at the other end is coupled by means of a reflectionless transition element to the end chamber in the branch guide. The series reactor in the main guide and the associated shunt reactor in the branch guide have reactances which

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are substantially equal at the mid-band frequency of the particular filter. If these reactances are of opposite sign, the reactors are separated by a transmission path having a phase shift approximately equal to an odd integral multiple of $\pi/2$ radians at the mid-band frequency. In this case the series reactor may, for example, be a capacitor and the shunt reactor an inductor. Alternatively, these reactances may be of the same sign, in which case the interposed transmission path has a phase shift approximately equal to an integral multiple of π radians.

As many as half a dozen or more branch filters may be connected to the main guide in the manner described to separate or combine a corresponding number of different frequency bands. The series coupling reactor introduces no appreciable impedance discontinuity into the main guide, thus avoiding off-channel reflection and consequently minimizing undesired interaction between the different channels. The disturbing effect at off-resonance frequencies of the phase shift in the portion of the main guide between its closed end and the point of connection of each branch filter is substantially eliminated by designing this portion of the guide as the first resonator of the filter and choosing its length so as to provide approximately the required stiffness, as mentioned above.

As compared with former microwave branching schemes, the present arrangement has greater mechanical flexibility in that the connecting coaxial line may be of substantially any desired length and, due to the symmetry of the coaxial line, the branch guides may make any desired angle with the main guide. The electrical flexibility may be increased by making either the shunt reactor or the series reactor, or both, variable. The shunt reactor, for example, may be constituted by an inductive post and a variable capacitor positioned alongside. The series reactor may, for example, be a variable capacitor constituted by a probe connected to the end of the inner conductor of the coaxial line and projecting for an adjustable distance into the main guide. Also, the transition element may conveniently be a second probe, connected to the other end of this inner conductor and projecting into the end chamber of the branch guide.

In addition to the first and second resonators described above, in the embodiment shown each filter comprises a number of other cavity resonators, each formed by a pair of equal reactors connected in shunt with the branch wave guide. These resonators are connected in tandem with

each other and with the second resonator by sections of wave guide each having a nominal phase shift equal to an odd integral multiple of $\pi/2$ radians at the mid-band frequency. Preferably, each of these connecting sections is adjusted in length to allow for the excess phase contributed by the resonators which it connects. Also, preferably, the stiffness of each of the resonators is adjusted to compensate for the stiffness contributed by the associated connecting section or sections. These corrections considerably improve the performance of the filter.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawings, of which:

Fig. 1 is a schematic circuit showing the general plan of a branching arrangement in accordance with the invention;

Fig. 2 is a top view of one embodiment of the invention comprising two channels;

Fig. 3 is a side view of the structure shown in Fig. 2;

Fig. 4 is an end view, partly broken away, of the structure shown in Figs. 2 and 3;

Fig. 5 is a simplified schematic diagram of the structure of Figs. 2, 3 and 4;

Fig. 6 is a lumped-element equivalent circuit for one of the filters shown in Fig. 5;

Fig. 7 shows separately one of the cavity resonator circuits of Fig. 6;

Fig. 8 is an equivalent circuit representing the resonator of Fig. 7 in the vicinity of the resonant frequency;

Fig. 9 is a curve useful in determining the required spacing between a pair of susceptible posts which define a cavity resonator for the filter;

Fig. 10 is a curve useful in determining the required diameter of the susceptible posts;

Fig. 11 is an equivalent circuit representing another cavity resonator of the filter in the vicinity of the resonant frequency;

Fig. 12 shows separately a third cavity resonator circuit of the filter;

Fig. 13 is an equivalent circuit representing the resonator of Fig. 12 in the vicinity of the resonant frequency;

Fig. 14 is the equivalent circuit obtained by substituting in Fig. 6 the resonator circuits shown in Figs. 8, 11 and 13;

Fig. 15 is an equivalent circuit representing a wave guide having a length equal to an odd number of quarter wavelengths;

Fig. 16 is a circuit, equivalent to the one shown in Fig. 14, useful in designing the filter; and

Fig. 17 shows typical insertion loss-frequency characteristics for the two-channel branching arrangement of Figs. 2, 3 and 4.

Taking up the figures in greater detail, Fig. 1 shows schematically the general plan of a branching arrangement in accordance with the present invention comprising a main transmission line 20 and a plurality of branch transmission lines 21, 22, 23 connected in shunt therewith at properly spaced intervals through the band-pass filters 24, 25 and 26, respectively. The main line 20 is short-circuited at one end by a strap 28. Wave energy including three bands centered, respectively at the frequencies f_1 , f_2 and f_k is either supplied to the line 20, or taken off, at the other end thereof, as indicated by the double-pointed arrow 29. The filters 24, 25 and 26 have mid-band frequencies of f_1 , f_2 and f_k , respectively. Therefore, if the frequencies f_1 , f_2 and f_k are fed into the main line 20 they are separated into the individual channels 21, 22 and 23, respectively.

Alternatively, energy of the frequencies f_1 , f_2 and f_k may be derived from the branch lines 21, 22 and 23 and combined in the main line 20. These possibilities are indicated by the double-pointed arrows designated f_1 , f_2 and f_k . There may, of course, be additional branches, as indicated by the dashed portion 30 of the line 20.

Each of the branch lines 21, 22 and 23 is connected to the main line 20 at a distance from the strap 28 approximately equal to an odd number of quarter wavelengths in the line 20 at the mid-band frequency of the filter associated with that particular branch. Thus, the branch 23 is connected at a distance equal to $(2n_k-1)\lambda_k/4$, where n_k is any integer and λ_k is the wavelength at the frequency f_k . Likewise, the distances to the lines 21 and 22 are, respectively $(2n_1-1)\lambda_1/4$ and $(2n_2-1)\lambda_2/4$, where n_1 and n_2 are integers and λ_1 and λ_2 are the wavelengths at the frequencies f_1 and f_2 , respectively. The integers n_1 , n_2 and n_k are, in general different. They are so chosen, as explained hereinafter, that the section of the main line 20 between the strap 28 and the point of connection of the particular branch has the proper stiffness to constitute the first cavity resonator of the filter associated with that branch.

Figs. 2, 3 and 4 show an embodiment of the invention suitable for use with microwaves. The arrangement comprises a main transmission line 35 and two branch lines 36 and 37. Each line is a rectangular wave guide of the hollow-pipe type, with unequal cross-sectional dimensions, adapted for the transmission of electromagnetic wave energy the electric field of which is oriented in a direction parallel with the shorter cross-sectional dimension, as indicated by the arrows E in Figs. 3 and 4. Part of the guide 35 has been omitted, as indicated in Fig. 2 by the break at the point 38. The guide 35 is closed at the right-hand end by a conductive plate 40 which may, for example, be soldered in place. Two bands of frequencies centered, respectively, at the frequencies f_1 and f_2 are fed into, or extracted from, the left-hand end of the guide 35, as indicated in Fig. 2 by the double-pointed arrow 41. The filters 42 and 43 associated, respectively, with the branch guides 36 and 37 have the mid-band frequencies f_1 and f_2 , respectively. Therefore, if energy is fed into the main guide 35, it will be separated on a frequency basis, f_1 going into the branch 36 and f_2 into the branch 37. Alternatively, if energy of the frequencies f_1 and f_2 is derived from the branches 36 and 37, it will combine in the main guide 35 without interaction between the two channels. These possibilities are indicated on Fig. 2 by the double-pointed arrows designated f_1 and f_2 .

Each of the branches 36 and 37 is connected to the main guide 35 at a distance from the shorting plate 40 approximately equal to an odd number of quarter wavelengths in the guide 35 at the mid-band frequency of the filter associated with that branch. Thus, in Fig. 2, the distances D_1 and D_2 are given by the formulas

$$D_1 = (2n_1 - 1)\lambda_1/4 \quad (1)$$

and

$$D_2 = (2n_2 - 1)\lambda_2/4 \quad (2)$$

where n_1 and n_2 are integers and λ_1 and λ_2 are the wavelengths in the guide 35 at the frequencies f_1 and f_2 , respectively. As explained more fully below, the number n_1 is so chosen that the length of line D_1 has the stiffness required for the first resonator in the filter 42. Likewise n_2 is so chosen that the length of line D_2 has the stiffness re-

quired for the first resonator in the filter 43. By thus using the stub end of the guide 35 as the first resonator in each filter, the unavoidable change with frequency in the phase shift associated with the portion (D_2-D_1) of the guide 35 between the filters 42 and 43 is used to advantage, instead of being permitted to disturb the performance of the filters.

Each of the branches 36 and 37 is connected to the main guide 35 by a rotary joint 45 so that the branch may be rotated to make any desired angle G with the guide 35, as shown in Fig. 2, thus making the structure physically flexible. As shown at the cut-away portion of Fig. 4, this rotary joint for the branch 37 is in the form of a short section of coaxial transmission line comprising a cylindrical outer conductor 46 and a concentric inner conductor 47. The outer conductor 46 is conductively connected to the periphery of a circular hole in one of the wider sides of the branch guide 37. The inner conductor 47 is supported in position by a disk 48 made of insulating material such as polystyrene. Another short conductive cylinder 50, having an inner diameter only slightly greater than the outer diameter of the conductor 46, is connected to the periphery of a circular hole in one of the wider sides of the main guide 35. The rotary joint 45 is formed by sliding the cylinder 46 into the cylinder 50. Because of the circular symmetry of the coaxial connecting line 45, rotation of the joint has no effect upon the electrical performance of the branching arrangement.

The inner conductor 47 is extended at one end into the branch 37 to form a probe 51 and at the other end into the main guide 35 to form a second probe 52. The location of the probe 51 with respect to the end 53 of the branch 37 and the length of the probe are chosen to provide a transition element which closely matches the impedance of the coaxial line 45 to that of the associated branch 37. Adjustment of the penetration of the probe 52 into the main guide 35 is provided by threading the end and screwing it into a tapped hole in the end of the inner conductor 47. A screwdriver slot in the end of the probe 52 facilitates adjustment. A hole in the side of the branch guide 37 opposite the probe 52, closed when not being used by a screw plug 54, is provided to permit the insertion of a screwdriver. Making the probe 52 adjustable permits the use of only one design for the section 55 of each filter.

Besides the section 55, each of the filters 42 and 43 comprises two other sections of wave guide 56 and 57, all connected in tandem and joined by means of flanges such as 58 and screws or bolts, not shown. Each filter comprises five cylindrical conductive posts or rods 60 through 64 transversely centered in the guide and extending all the way across between the wider sides parallel to the electric field E . Posts 61 and 62 are associated with section 56 and posts 63 and 64 with section 57. Each of these pairs of posts, such as 61, 62, forms in effect a cavity resonator in the branch guide. The resonators are connected in tandem by the intervening portions of the branch guide. The transversely centered frequency-adjusting screws 65 and 67, which extend through one of the wider sides of the branch guide, are located, respectively, mid-way between each pair of posts to provide an adjustment of the resonant frequency of the associated resonator. A similar screw 68 is associated with the section 55. The section 55 has only a single post 75

60, the susceptance of which may be adjusted by means of the screw 69, located beside the post 60 in the same transverse plane. The chamber 59 formed in the branch 37 between the end 53 and the post 60, together with the coaxial line section 45, constitutes the second resonator of the filter 43. The manner in which the diameters and locations of the posts 60 through 64 are determined, in order to provide the desired band-pass characteristics for the filters 42 and 43, will be explained below. It will be apparent from the above description that the two filters are physically alike, except for the differences in dimensions which are required because they have different mid-band frequencies. It is also to be understood that there may be more than two branching filters.

A suggested design technique for determining the dimensions of the component parts of the branching arrangement shown in Figs. 2, 3, and 4 will now be presented, with the aid of a number of simplified diagrams to which reference will be made. The procedure will be to obtain an equivalent lumped-element circuit for the entire structure. Since the design of lumped-element filter circuits is well known, the design of the structure will then be apparent.

Fig. 5 is a schematic diagram of the branching arrangement reduced to its essentials. For simplicity, the two branch wave guides 36 and 37, shown only in outline, are represented as being connected to opposite sides, instead of the same side, of the main wave guide 35, and each of the branches has been swung through an angle of 90 degrees so that it is parallel with the main guide. These modifications will not affect the performance of the structure.

Considering more particularly the filter 43 associated with the branch 37, each filter comprises four cavity resonators 71, 72, 73, and 74. The resonator 71 is formed by the inductive posts 63 and 64 of the same diameter H , spaced apart a distance D_3 slightly less than a half wavelength, λ_g , in the branch 37 at the frequency f_2 . In the same manner, the resonator 72 is formed by the posts 61 and 62, with similar spacing D_5 . The resonator 73 is constituted by the end chamber 59, of length D_7 slightly less than $\lambda_g/2$, and the coaxial line section 45, of length D_8 approximately equal to $\lambda_0/4$, where λ_0 is the wavelength in air at the frequency f_2 . Resonator 74 is the portion of the main guide 35 between the shorting plate 46 and the probe 52, with a length D_2 . The resonators 71 and 72 are connected by a section of guide 77 having a length D_4 nominally equal to an odd number, say three, of quarter wavelengths $\lambda_g/4$. The resonators 72 and 73 are connected by a section 78 of similar length D_6 .

The four-terminal network shown in Fig. 6, with input terminals 81, 82 and output terminals 83, 84, is a lumped-element equivalent circuit for the filter 43 of Fig. 5. The shunt inductances 60' through 64', spaced along the line as shown, represent, respectively the posts 60 through 64. The capacitance 85 represents that effective between the probe 52 and the main guide 35. The parallel-connected capacitance C_1 and inductance L_1 in the shunt branch 87 represent the shorted section of the main guide 35 of length D_2 , which constitutes the resonator 74. The resonators 71, 72, and 73, and the connecting sections of line 77 and 78, are given the same designations as in Fig. 5.

How to determine the required lengths D_3 and

D_5 of the resonators 71 and 72, respectively, and the diameters of the posts 61 through 64 will now be considered. As shown in Fig. 6, each of these resonators consists of two spaced, equal, shunt inductances. The portion of Fig. 6 between the points 88, 89 and 90, 91, which constitutes the resonator 71, is shown separately in Fig. 7. As indicated on the figure, at the frequency f_2 each of the inductances 63' and 64' has a susceptance equal to $-j2b_1$, and the connecting section of line of length D_3 and characteristic impedance R_0 has a phase shift ϕ_1 .

It can be shown by matrix or other methods that, in the vicinity of the resonant frequency f_2 of the resonator, the network of Fig. 7 can be accurately represented by the equivalent circuit shown in Fig. 8. The network of Fig. 8 consists of a central shunt branch 92, comprising the parallel combination of a capacitance C_1 and an inductance L_1 , and on each side thereof a section of transmission line of length D_3 having a characteristic impedance R_0 and a phase shift ϕ_1 , as indicated.

This phase shift ϕ_1 may be called the excess phase shift associated with the resonator 71. As explained below, the excess phase shift associated with the resonators is allowed for in the filter design by adjusting the lengths of the connecting sections of line. Assuming that the susceptance b_1 is known, the phase shift ϕ_1 may be found from the expression

$$\phi_1 = \tan^{-1} \left| \frac{1}{b_1} \right| \quad (3)$$

The required distance D_3 is found from the formula

$$D_3 = (\pi - \phi_1) \frac{\lambda_g}{2\pi} \quad (4)$$

where π has its usual significance.

The normalized stiffness S_1 of the branch 92 may be found from the expression

$$S_1 = R_0 \sqrt{\frac{C_1}{L_1}} \quad (5)$$

The following formula relates S_1 to the susceptance b_1 :

$$S_1 = 2\pi b_1 \sqrt{b_1^2 + 1} \left(1 - \frac{\phi_1}{\pi} \right) \left(\frac{\lambda_g}{\lambda_0} \right)^2 \quad (6)$$

It will be noted that the only factors in Equation 6 which depend upon frequency are λ_g and λ_0 . If we introduce a parameter M defined as

$$M = 2\pi b_1 \sqrt{b_1^2 + 1} \left(1 - \frac{\phi_1}{\pi} \right) \quad (7)$$

Equation 6 becomes

$$S_1 = M \left(\frac{\lambda_g}{\lambda_0} \right)^2 \quad (8)$$

A curve showing the relationship between M and b_1 is given in Fig. 9.

The length D_3 may be determined as follows. In any specific filter design, the values of C_1 and L_1 , as well as the resonant frequency f_2 of the resonator 71, will be known. The required normalized stiffness S_1 is then found from Equation 5. The wavelengths λ_g and λ_0 can be calculated or measured. Therefore, Equation 8 may be solved for M . The corresponding value of b_1 , read from the curve of Fig. 9, is substituted in Equation 3 to find ϕ_1 . This value of ϕ_1 is then used in Equation 4 to find D_3 .

At any frequency such as f_2 where only the dominant mode can be propagated through the wave guide, the absolute value of the suscept-

ance b_1 of a cylindrical post of diameter H , such as 64 shown in Figs. 3 and 5, is given by the expression

$$|b_1| = K \left(\frac{\lambda_g}{2a} \right) \quad (9)$$

where a is the longer inside cross-sectional dimension of the wave guide 37, and K is a parameter which depends upon the ratio of H to a . An experimentally determined curve of K plotted against H/a , using logarithmic scales, is given in Fig. 10. The required diameters of the posts can thus be found from Equation 9 with the aid of the curve of Fig. 10.

The diameter of each of the posts 61 and 62, which form the resonator 72, and the spacing D_5 therebetween may be determined in the same way as just described in connection with the resonator 71. The resonator 72, which has a normalized stiffness S_2 , may be represented, as shown in Fig. 11, by a shunt branch 93 comprising the parallel combination of a capacitance C_2 and an inductance L_2 with equal sections of transmission line of length D_{10} and phase shift ϕ_2 on each side thereof.

The network shown in Fig. 12 represents the resonator 73, which corresponds to the portion of Fig. 6 between the points 94, 95 and 96, 97 with the shunt branch 87 omitted. The series capacitance 85 is separated from the shunt inductance 60' by a section of transmission line of length D_7 plus D_8 , which has a characteristic impedance R_0 and a phase shift θ_3 at the frequency f_2 , as indicated. Since the elements 85 and 60' have reactances which are opposite in sign, θ_3 must be equal to an odd integral multiple of $\pi/2$ radians and, in the present example, is equal to slightly less than $3\pi/2$.

At the resonant frequency f_2 , the capacitance 85 has a reactance $-jx$, and the inductance 60' has a susceptance $-jb_3$. In order to provide a resonator of minimum loss, these quantities must each be equal in magnitude to a parameter U , to be determined, as explained below. In equation form

$$|x| = |b_3| = U \quad (10)$$

It can be shown that, in the vicinity of the resonant frequency f_2 , the network of Fig. 12 can be accurately represented by the equivalent circuit shown in Fig. 13. The network of Fig. 13 comprises two sections of transmission line of length D_{11} and D_{12} , respectively, and, at their junction, a shunt branch 99 consisting of the parallel combination of a capacitance C_3 and an inductance L_3 . Each of the lines has a characteristic impedance R_0 , the section D_{11} has a phase shift α , and D_{12} has a phase shift equal to $\alpha + \pi/2$, as indicated, where

$$\alpha = \frac{1}{2} \tan^{-1} \left(\frac{2}{U} \right) \quad (11)$$

Since the values of C_3 and L_3 will be known from the filter design, the normalized stiffness S_3 of the resonator 73 can be found from the formula

$$S_3 = R_0 \sqrt{\frac{C_3}{L_3}} \quad (12)$$

and is related to the parameter U by the expression

$$S_3 = \pi U \sqrt{U^2 + 4} \left(\frac{D_7 \lambda_g + D_8}{\lambda_0^2} \right) \quad (13)$$

It is seen from Equation 13 that S_3 depends upon D_7 , D_8 , and U , which, by Equation 10, depends upon the magnitude of x and b_3 . Since the effec-

tive lengths D_7 and D_8 are difficult to determine, it is preferable that adjustments of x and b_2 be provided so that the desired value of S_3 may be obtained. Therefore, the probe 52, Fig. 4, is made adjustable to vary the reactance x , and the adjusting screw 69 is provided to vary the susceptance b_3 .

The resonator 74, represented in Fig. 6 by the shunt elements C_4 and L_4 , is constituted by the shorted end section having a length D_2 given by Equation 2. The required values of C_4 and L_4 will be known from the filter design. The normalized stiffness S_4 is given by

$$S_4 = R_m \sqrt{\frac{C_4}{L_4}} \quad (14)$$

where R_m is the characteristic impedance of the guide 35. In order to find the proper integer n_2 to use in Equation 2, use is made of the relationship

$$S_4 = (2n_2 - 1) \frac{\pi}{4} \left(\frac{\lambda_2}{\lambda_0} \right)^2 \quad (15)$$

and n_2 is so chosen as to satisfy the equation as nearly as possible.

When the equivalent circuits for the resonators 71, 72, and 73, as given in Figs. 8, 11, and 13, respectively, are substituted in Fig. 6, the equivalent circuit shown in Fig. 14 is obtained. The circuit comprises four parallel-resonant shunt branches 87, 99, 93, and 92 separated by transmission line sections of length D_{12} , D_{13} , and D_{14} , respectively, each having a phase shift equal to an odd integral multiple of $\pi/2$ radians at the frequency f_2 . This number may, for example, be three. The length D_{12} between the branches 87 and 99 is the one similarly designated in Fig. 13, having a phase shift equal to $\alpha + \pi/2$. As shown in Fig. 14, the length D_{13} is made up of the lengths D_{11} , D_6 , and D_{10} . The lengths D_{10} and D_{11} are shown, respectively, on Figs. 11 and 13. In determining the length D_6 , which is the physical length of the line separating the cavities 72 and 73, as shown in Fig. 5, the phase shift of the sections D_{10} and D_{11} must be taken into account. For example, if D_{13} is to have a phase shift of $3\pi/2$ radians, the length of line D_6 is so chosen that its phase shift ϕ_6 is

$$\phi_6 = 3\pi/2 - \phi_2 - \alpha \quad (16)$$

In a similar manner, in selecting the length D_4 of the line between the resonators 71 and 72, the phase shift associated with D_9 and D_{10} is allowed for. When the excess phase shift associated with the resonators is thus taken into consideration in determining the lengths of the connecting line sections D_4 and D_6 , the transmission characteristic of the filter is considerably improved.

Another correction which improves the transmission characteristic involves the phase shift of the connecting lines at frequencies other than the mid-band frequency. Previous design methods have assumed that each of these connecting sections, such as 77 and 78 in Fig. 5, has a constant phase shift of $\pi/2$ radians, or an odd integral multiple thereof, at all frequencies within the transmission band of the filter. However, the phase shift has this value only at the mid-band frequency. This assumption, therefore, introduces an error, especially important if the band is wide, which causes a degradation of the transmission characteristic. However, this error can be largely eliminated by making a compensating adjustment of the normalized stiffness of each of the resonators which the line section couples.

How to determine the magnitude of this correction will be explained in connection with Fig. 15, which shows schematically an equivalent circuit representing a wave guide having a length equal to an odd number of quarter wavelengths. The box 100, as indicated therein, represents a section of transmission line of characteristic impedance R_0 having a phase shift of ϕ_K radians, where ϕ_K is equal to an odd multiple of $\pi/2$ and is constant with frequency. At each end of the line section 100 is a shunt branch 101 comprising a capacitance C and an inductance L connected in parallel. The normalized stiffness S of each of the branches 101 is given by the expression

$$S = R_0 \sqrt{\frac{C}{L}} = (2n - 1) \frac{\pi}{4} \left(\frac{\lambda_c}{\lambda_0} \right)^2 \quad (17)$$

where the quantity $2n - 1$ is the number of $\pi/2$ radians of phase shift in the connecting section. The required correction is made by subtracting S from the normalized stiffness determined from the filter design for each of the resonators at the ends of the connecting section. For example, in Fig. 5, if the normalized stiffness of the resonator 72, as given by the theoretical design, is S_2' and the normalized stiffnesses of the connecting sections 77 and 78, as computed by Equation 17, are S_A and S_B , respectively, the corrected normalized stiffness S_2 of the resonator is

$$S_2 = S_2' - S_A - S_B \quad (18)$$

For design purposes, the circuit of Fig. 14 may be transformed into the equivalent circuit shown in Fig. 16 comprising a ladder network in tandem with a section of lossless transmission line 93. The line 93 has a characteristic impedance R_0 and a phase shift ϕ_s , equal to the total phase shift of the connecting line sections D_{12} , D_{13} , and D_{14} in Fig. 14. The shunt branches 87 and 93 in Fig. 16 are the same as those similarly designated in Fig. 14. The shunt branches 92 and 99 of Fig. 14 are represented in Fig. 16 by the series branches 92' and 99', respectively. The branch 92' comprises a capacitance C_1' and an inductance L_1' connected in series, and the branch 99' is made up of the series combination of a capacitance C_3' and an inductance L_3' . The elements in the series branches 92' and 99' are related to the corresponding elements in the shunt branches 92 and 99 as follows:

$$\frac{L_1'}{C_1'} = \frac{L_1}{C_1} = \frac{L_3'}{C_3'} = \frac{L_3}{C_3} = R_0^2 \quad (19)$$

The section of line 93 in Fig. 16 does not contribute to the insertion loss of the filter, and may be neglected from this standpoint. The required values of the component elements comprising the ladder portion of the circuit, to obtain the desired insertion loss, may be calculated by any suitable method. One method, which provides a filter with a transmission characteristic of the maximally-flat type, is described in the paper by W. W. Mumford in the Bell System Technical Journal, vol. XXVII, No. 4, October, 1948, pages 684 through 709, entitled, "Maximally-flat Filters in Waveguide." Next, the circuit is transformed into the equivalent circuit of Fig. 14, and the theoretical values of the normalized stiffness S_1' , S_2' , S_3' , and S_4' associated, respectively, with the shunt branches 92, 93, 99, and 87 are found. These values are then corrected for the excess phase shift of the resonant cavities and the phase shift in the connecting sections of line, in the manner described above, to give the normalized stiffnesses S_1 , S_2 , S_3 , and S_4 required for the cavity resonators 71, 72, 73, and 74, respectively.

The physical dimensions of the wave-guide structure shown in Figs. 1, 2, and 3 may then be computed, as explained above.

Typical insertion loss-frequency characteristics for a two-channel branching arrangement designed in accordance with the invention are shown in Fig. 17, where the loss in decibels is plotted against the frequency in megacycles per second. Each channel passes a twenty-megacycle band. The solid-line curve 102 is the characteristic of the lower channel, centered at 3950 megacycles, and the broken-line curve 103 is that of the upper channel, centered at 4030 megacycles. The wave guide used was rectangular in cross section and was made of brass, with a wall thickness of 0.064 inch and inside dimensions of 1.145 inches by 2.290 inches. It is seen that the channels have low loss in the band and adequate suppression outside of the band. Of course, one or more similar channels may be added, as required, either below the lower channel or above the upper channel.

What is claimed is:

1. In combination, a first wave guide closed at one end, a second wave guide closed at one end, means for introducing electromagnetic waves of a selected frequency into one of said guides at the other end thereof, means for extracting said waves at the other end of the other of said guides, a shunt reactor in said second guide forming an end chamber therein, a coaxial transmission line coupling said chamber to said first guide at a distance from the closed end thereof approximately equal to an odd integral number of quarter wavelengths at said frequency, and a conducting element connected to the inner conductor of said coaxial line and extending into the electromagnetic field of said first guide to form a series reactor coupling said coaxial line to said first guide, the reactances of said reactors being substantially equal in magnitude at said frequency and the transmission path between said reactors having a phase shift such that said chamber, said coaxial line and said series reactor constitute a cavity resonator resonant at said frequency.
2. The combination in accordance with claim 1 in which said shunt reactor has an inductive reactance at said frequency.
3. The combination in accordance with claim 1 in which said shunt reactor includes a conductive post extending across said second guide.
4. The combination in accordance with claim 3 in which said shunt reactor also includes a variable capacitor.
5. The combination in accordance with claim 1 in which said series reactor is a capacitor.
6. The combination in accordance with claim 1 in which said reactances are of opposite sign and said transmission path has a phase shift approximately equal to an odd integral multiple of $\pi/2$ radians at said frequency.
7. The combination in accordance with claim 1 which includes means for adjusting the reactance of said shunt reactor.
8. The combination in accordance with claim 1 which includes means for adjusting the reactance of said series reactor.
9. The combination in accordance with claim 1 which includes means for adjusting the reactance of each of said reactors.
10. The combination in accordance with claim 1 in which said second guide includes also a pair of equal shunt reactors longitudinally spaced therein to define a second cavity resonator resonant at said frequency, said second resonator be-

ing separated from said first-mentioned shunt reactor by a transmission path having a phase shift approximately equal to an odd integral multiple of $\pi/2$ radians at said frequency and the stiffness of said second resonator being adjusted to compensate for the stiffness contributed by said last-mentioned transmission path.

11. The combination in accordance with claim 1 in which the outer conductor of said coaxial line comprises two conductive cylinders, one of said cylinders being conductively connected at one end to said first guide, the other of said cylinders being conductively connected at one end to said second guide, and one of said cylinders fitting over the other to form a rotary joint.

12. In combination, a wave filter, a main wave guide, and means for coupling said filter to said guide, said filter comprising a section of wave guide closed at one end and a shunt reactor therein forming an end chamber, and said coupling means comprising a coaxial transmission line, a transition element for coupling said coaxial line to said chamber substantially without reflection, and a conducting element connected to the inner conductor of said coaxial line and extending into the electromagnetic field of said main guide to form a series reactor coupling said coaxial line to said main guide, said two reactors having reactances which are substantially equal in magnitude at the mid-band frequency of said filter and the transmission path between said reactors having a phase shift approximately equal to an integral multiple of $\pi/2$ radians at said frequency.

13. The combination in accordance with claim 12 in which said shunt reactor has an inductive reactance at said frequency.

14. The combination in accordance with claim 12 which includes means for adjusting the reactance of said shunt reactor.

15. The combination in accordance with claim 12 which includes means for adjusting the reactance of said series reactor.

16. The combination in accordance with claim 12 in which said conducting element is a probe projecting an adjustable distance into said main guide.

17. The combination in accordance with claim 12 in which said transition element comprises a probe connected to the inner conductor of said coaxial line and projecting into said chamber.

18. The combination in accordance with claim 12 in which said shunt reactor comprises an inductor and a variable capacitor positioned side by side.

19. The combination in accordance with claim 12 in which said main guide is closed at one end and said coaxial line is coupled to said main guide at a distance from the closed end thereof approximately equal to an odd integral number of quarter wavelengths at said frequency.

20. The combination in accordance with claim 12 in which said filter includes also a pair of equal shunt reactors longitudinally spaced within said section of guide to define a cavity resonator resonant at said frequency, said resonator being separated from said first-mentioned shunt reactor by a transmission path having a phase shift approximately equal to an odd integral multiple of $\pi/2$ radians at said frequency and the stiffness of said resonator being adjusted to compensate for the stiffness contributed by said last-mentioned transmission path.

21. A filter comprising a main wave guide closed at one end, a branch wave guide closed at

one end, a shunt reactance in said branch guide forming an end chamber therein, and means for coupling said chamber to said main guide at a point located from the closed end thereof an integral number of quarter wavelengths at the mid-band frequency of the filter, said coupling means including a section of coaxial transmission line, a transition element for coupling said coaxial line to said branch guide substantially without reflection and a conducting element connected to the inner conductor of said coaxial line and extending into said main guide to form a series reactance coupling said coaxial line to said main guide, said reactances being approximately equal in magnitude but of opposite sign at said frequency and being separated by a transmission path having a phase shift approximately equal to an odd integral multiple of $\pi/2$ radians at said frequency.

22. A filter in accordance with claim 21 which includes also a pair of equal shunt reactances longitudinally spaced within said branch guide to define a cavity resonator resonant at said frequency, said resonator being separated from said first-mentioned shunt reactance by a transmission path having a phase shift approximately equal to an odd integral multiple of $\pi/2$ radians at said frequency and the stiffness of said resonator being adjusted to compensate for the stiffness contributed by said last-mentioned transmission path.

23. A microwave branching arrangement comprising a main wave guide closed at one end, a plurality of branch wave guides each closed at one end, a shunt inductor in each of said branch guides forming an end chamber therein, and means for coupling said chambers to said main guide at different points each located an odd integral number of quarter wavelengths from the closed end thereof at the mid-band frequency transmitted by the associated branch guide, each of said coupling means comprising a section of coaxial transmission line and probes connected to the respective ends of the inner conductor thereof, one of said probes projecting into the associated chamber to provide a substantially reflectionless transition element, the other of said probes projecting into said main guide a distance to provide a capacitance approximately equal in magnitude to the reactance of the inductor in the associated branch guide at the mid-band frequency thereof, and the phase shift of the transmission path between said capacitance and said associated inductor being approximately equal to an odd integral multiple of $\pi/2$ radians at the mid-band frequency of said associated branch guide.

24. A branching arrangement comprising a main wave guide closed at one end, a plurality of branch wave guides each closed at one end, a shunt reactor in each of said branch guides forming an end chamber therein, coaxial transmission lines connecting said chambers, respectively, to different points on said main guide each located an integral number of quarter wavelengths from the closed end thereof at the mid-band frequency transmitted by the associated branch guide, and means for coupling each of said coaxial lines to the associated chamber and to said main guide, each of said coaxial lines together with the associated coupling means and chamber forming a cavity resonator which is resonant at the mid-band frequency of said associated branch guide.

25. The combination in accordance with claim

12 in which said reactances are of opposite sign and said integral multiple is odd.

26. A filter in accordance with claim 21 in which said integral number of quarter wavelengths is odd.

27. A filter in accordance with claim 26 in which said series reactance is capacitive.

28. In combination, a first wave guide closed at one end, a second wave guide closed at one end, means for introducing electromagnetic waves of a selected frequency into one of said guides at the other end thereof, means for extracting said waves at the other end of the other of said guides, a shunt reactor in said second guide forming an end chamber therein, a coaxial transmission line coupling said chamber to said first guide at a distance from the closed end thereof approximately equal to an integral number of quarter wavelengths at said frequency, and a conducting element connected to the inner conductor of said coaxial line and extending into the electromagnetic field of said first guide to form a series reactor coupling said coaxial line to said first guide, the reactances of said reactors being substantially equal magnitude at said frequency, the transmission path between said reactors having a phase shift such that said chamber, said coaxial line and said series reactor constitute a cavity resonator resonant at said frequency, and said shunt reactor including a conductive post extending across said second guide and a variable capacitor.

29. In combination, a first wave guide closed at one end, a second wave guide closed at one end, means for introducing electromagnetic waves of a selected frequency into one of said guides at the other end thereof, means for extracting said waves at the other end of the other of said guides, a shunt reactor in said second guide forming an end chamber therein, a coaxial transmission line coupling said chamber to said first guide at a distance from the closed end thereof approximately equal to an integral number of quarter wavelengths at said frequency, and a conducting element connected to the inner conductor of said coaxial line and extending into the electromagnetic field of said first guide to form a series reactor coupling said coaxial line to said first guide, the reactances of said reactors being substantially equal in magnitude at said frequency, the transmission path between said reactors having a phase shift such that said chamber, said coaxial line and said series reactor constitute a cavity resonator resonant at said frequency, said reactances being of opposite sign, and said transmission path having a phase shift approximately equal to an odd integral multiple of $\pi/2$ radians at said frequency.

30. In combination, a first wave guide closed at one end, a second wave guide closed at one end, means for introducing electromagnetic waves of a selected frequency into one of said guides at the other end thereof, means for extracting said waves at the other end of the other of said guides, a shunt reactor in said second guide forming an end chamber therein, a coaxial transmission line coupling said chamber to said first guide at a distance from the closed end thereof approximately equal to an integral number of quarter wavelengths at said frequency, and a conducting element connected to the inner conductor of said coaxial line and extending into the electromagnetic field of said first guide to form a series reactor coupling said coaxial line to said first guide, the reactances of said reactors being sub-

stantially equal in magnitude at said frequency, the transmission path between said reactors having a phase shift such that said chamber, said coaxial line and said series reactor constitute a cavity resonator resonant at said frequency, said second guide including also a pair of equal shunt reactors longitudinally spaced therein to define a second cavity resonator resonant at said frequency, said second resonator being separated from said first-mentioned shunt reactor by a transmission path having a phase shift approximately equal to an odd integral multiple of $\pi/2$ radians at said frequency, and the stiffness of said second resonator being adjusted to compensate for the stiffness contributed by said last-mentioned transmission path.

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