

Dec. 13, 1960

K. S. PACKARD
MICROWAVE CIRCUITS

2,964,718

Filed March 21, 1955

5 Sheets-Sheet 1

FIG. 1

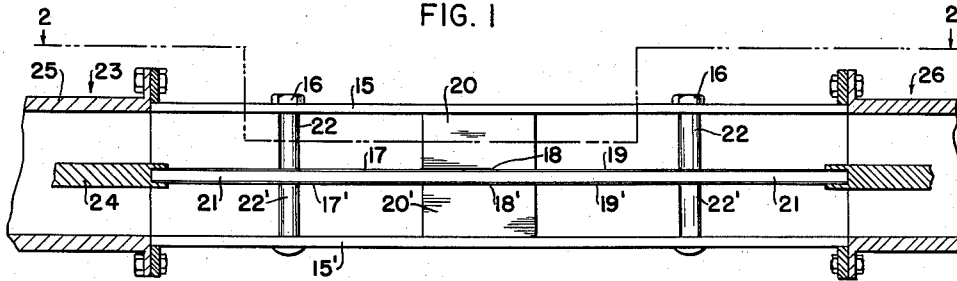


FIG. 2

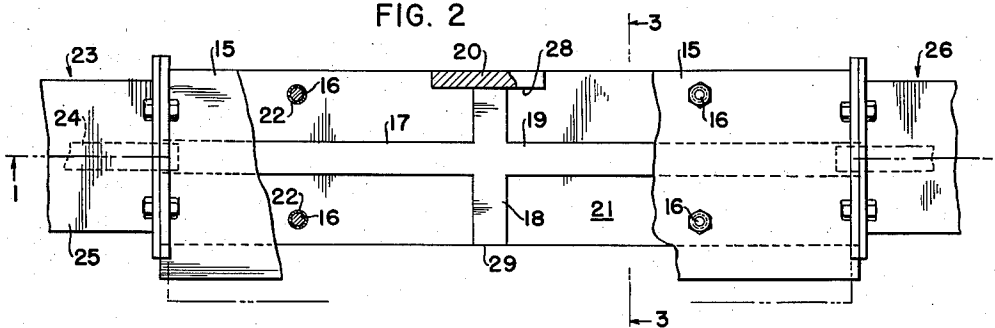


FIG. 3

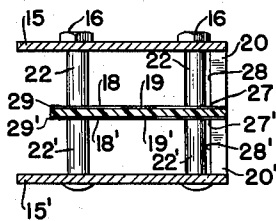


FIG. 4

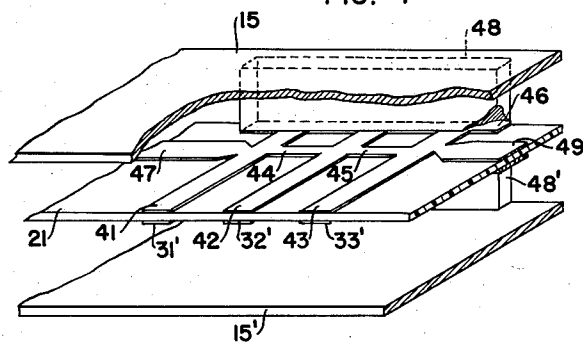
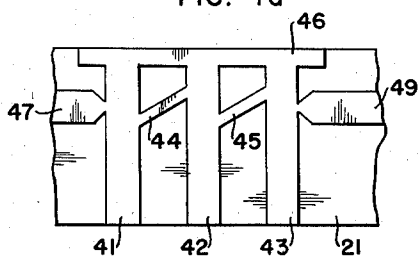


FIG. 4a



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FIG. 5

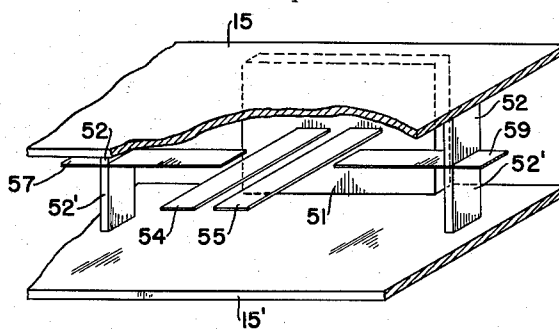


FIG. 7

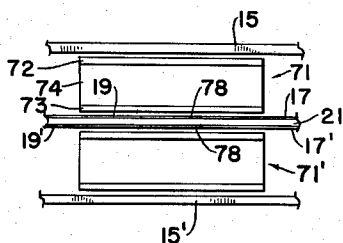
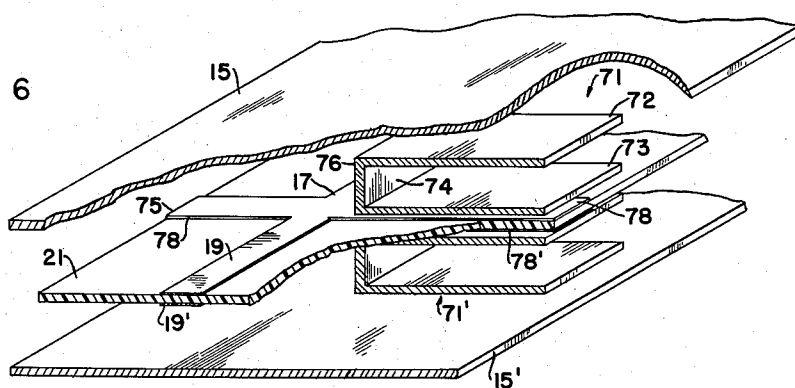


FIG. 6



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FIG. 8

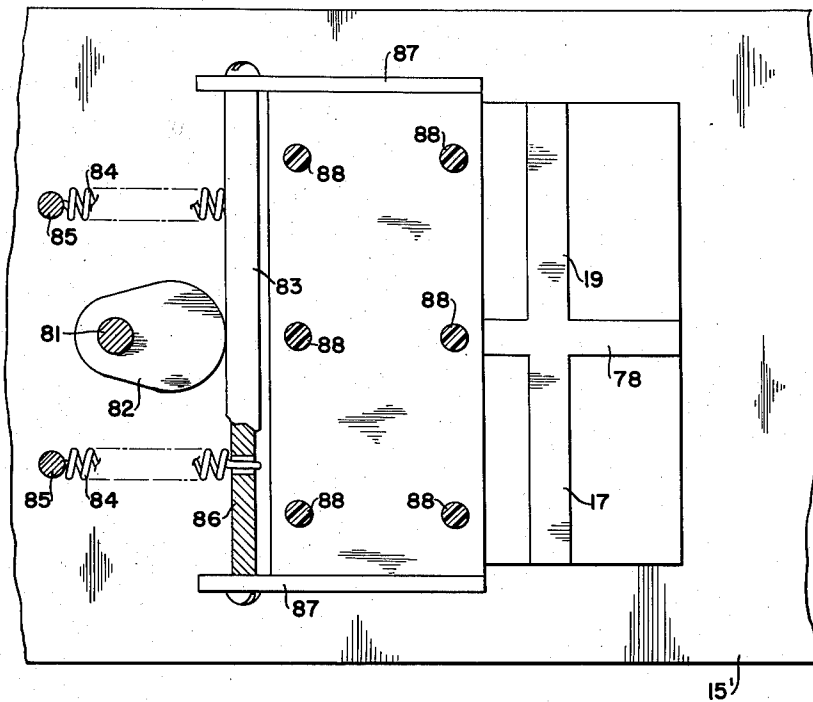
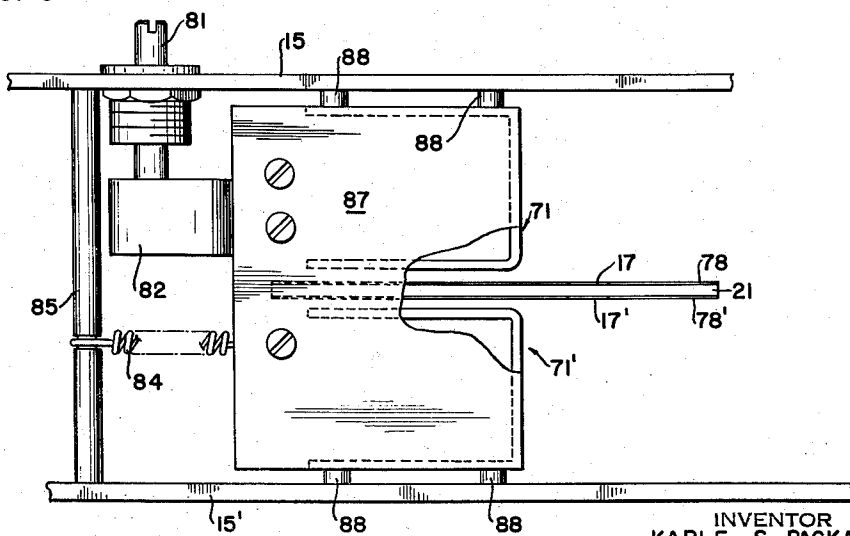


FIG. 9



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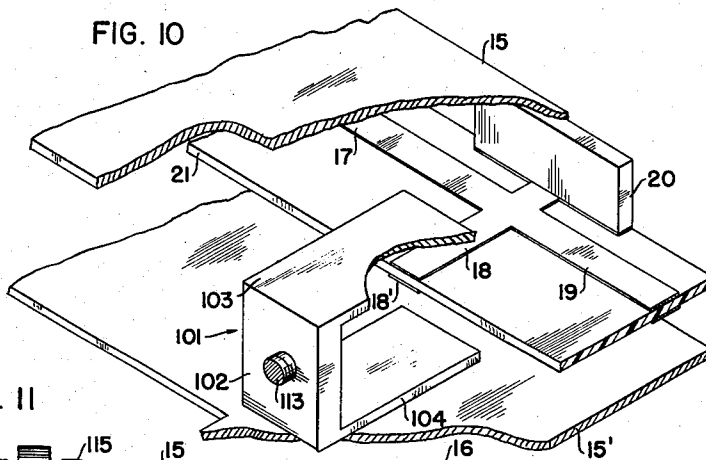
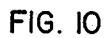


FIG. 11

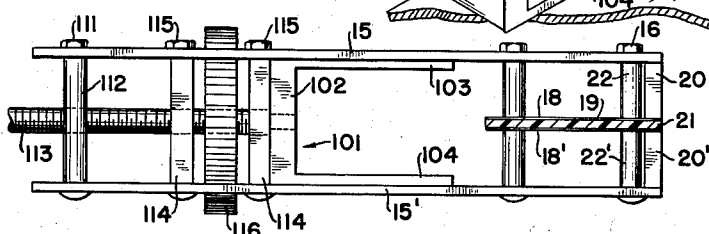
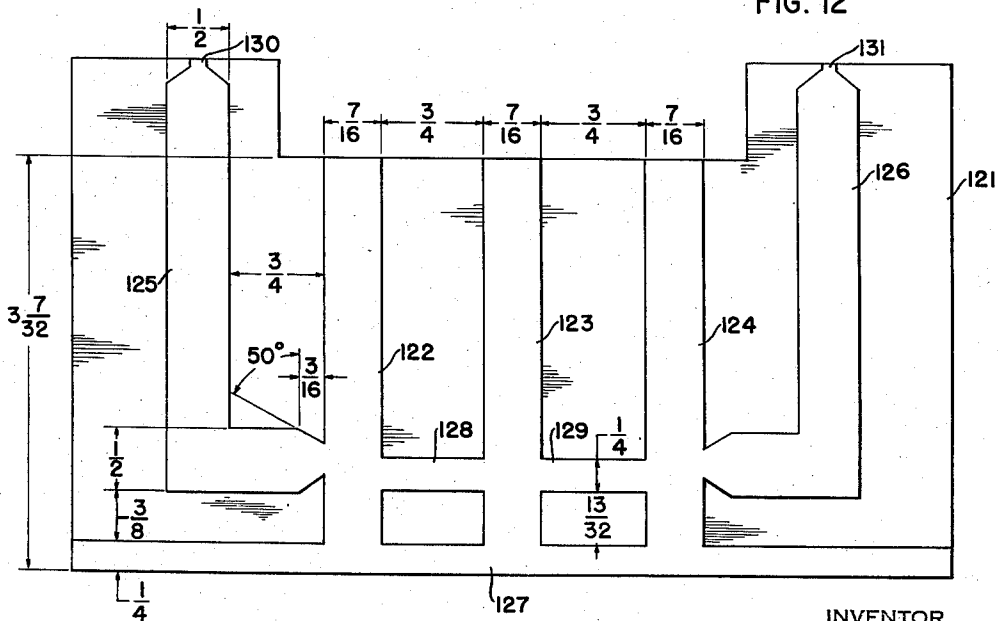


FIG. 12



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FIG. 13

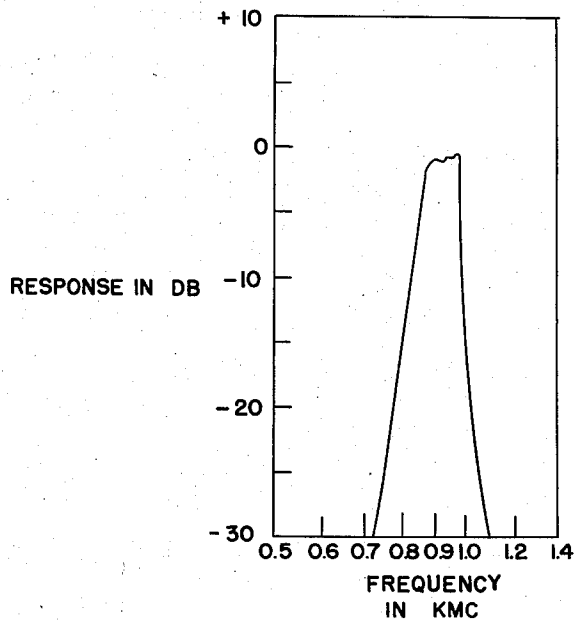


FIG. 15a

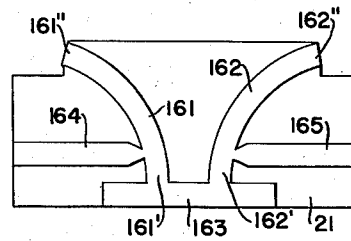


FIG. 15b

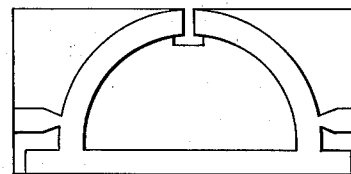
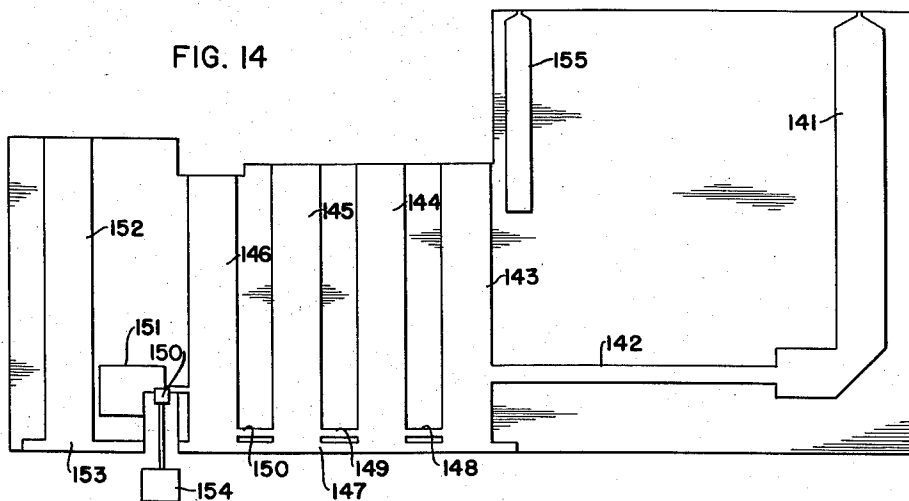


FIG. 14



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Filed Mar. 21, 1955, Ser. No. 495,577

11 Claims. (Cl. 333—73)

This invention relates to microwave frequency-selective circuits, and particularly to such circuits formed of and incorporated in symmetrical strip transmission lines of the substantially air-dielectric type.

Application Serial No. 469,454, filed November 17, 1954, by Eugene G. Fubini and John N. Dyer for "Microwave Circuits," describes and claims such frequency-selective circuits employing half-wave resonant elements or multiples thereof. The present invention employs resonant elements which are a quarter-wavelength long or an odd multiple thereof.

At microwave frequencies it is common to employ coaxial line or waveguide for the transmission of electromagnetic energy. In some cases, particularly at lower frequencies and for short distances, parallel wire transmission line is employed. It has also been suggested to employ an unsymmetrical transmission line consisting of a wire or conductive strip supported above a ground plane. An improved form of symmetrical strip transmission line having low losses is disclosed in application Serial No. 380,674, filed September 17, 1953, by Eugene G. Fubini for "Strip Transmission Line."

In microwave circuits, as in the case of lower frequency circuits, frequency-selective circuits are often required. They find use as components of filters, in amplifiers and as the resonant portions of oscillators, etc. At microwave frequencies such frequency-selective circuits are usually short lengths of transmission line. Parallel wire, coaxial, and waveguide transmission lines have been used in this manner. Coaxial or waveguide line is inherently shielded, but parallel wire line is not. Thus, if energy from a parallel wire section is to be isolated from adjacent electrical circuits, a separate shield is required. Unsymmetrical strip transmission line is not well suited to use in a frequency-selective network, since it radiates energy at discontinuities and thus introduces losses which would seriously impair its usefulness for this purpose.

The present invention is particularly directed to frequency-selective circuits or filters of the resonant type, employing tuned sections, as distinguished from those of the non-resonant type. Simple frequency-selective circuits of this type may consist of a single resonant section, or several resonant sections mutually coupled, through which the electromagnetic energy passes.

If filters of this type are constructed of coaxial line, each resonant section is enclosed within its outer conductor. Thus it is necessary to provide means for coupling into and out of the resonant sections. For all but the very simplest filters, the construction becomes complicated and expensive.

A frequency-selective waveguide circuit is usually made in the form of three or more orthogonal pairs of conductive walls proportioned in modal relation to the wavelength of the frequency to be selected. For best results the internal metallic surfaces should be smooth and highly conductive. Such structures are expensive to fabricate, particularly in all but the simplest filters, and the mechanical tolerances are tight.

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The difficulties in designing and constructing microwave filters are particularly acute in the case of band pass filters requiring several resonant circuits to obtain a sufficiently broad band with adequate selectivity outside the pass band. Such filters should ordinarily have as low an insertion loss as possible within the pass band, and this requires the use of high Q circuits. If heretofore conventional methods are employed, such filters are usually bulky and expensive, and in many cases it is very difficult to obtain the desired operating characteristics.

It is also important in many applications to be able to vary the tuning of a frequency-selective circuit over a desired frequency range. While in many cases this is possible with conventional constructions, the circuits are usually expensive and often unduly bulky. Also, impedance transforming is often required to meet the requirements of a given application.

In accordance with the present invention, frequency-selective circuits or filters of the resonant type are provided which employ so-called quarter-wavelength tuned sections. It is a primary object of the invention to provide such frequency selective networks or filters for use in the microwave region which can readily be fabricated at low cost, are efficiently shielded and simple to excite, and have high electrical efficiency. It is a further object to provide a structure in which a plurality of filter sections are conveniently and simply coupled together to form band pass filters of highly desirable characteristics. In addition, it is an object of this invention to provide a filter structure in which tuning means and impedance transforming configurations may be conveniently and simply incorporated.

To this end, in accordance with the present invention, one or more filter sections, and advantageously input and output transmission line sections also, are formed of conductive strip supported midway between a pair of conductive surfaces, the pair of conductive surfaces being maintained at a common potential to form ground planes and the volume between the strip sections and the conductive surfaces being largely gaseous. Thus, the filter sections, and advantageously the input and output transmission line sections also, are made of portions of symmetrical strip transmission line of the substantially air-dielectric type. Advantageously the construction described in application Serial No. 380,674, supra, may be employed.

The filter strip sections are resonant within the operating range of the filter, each strip section being elongated and having a length which is approximately equal to an odd integral multiple of quarter-wavelengths at the resonant frequency thereof, it being understood that the term "multiple" includes one.

It is particularly contemplated to employ quarter-wavelength sections which are short-circuited at one end thereof. However, it is possible to employ open-circuited quarter-wavelength sections, particularly in conjunction with short-circuited sections to obtain a desired overall characteristic. Short-circuited sections may be constructed by very simple means for short-circuiting one end of the central conductor to the ground planes. The short-circuiting means may be stationary or movable, the latter providing a means for varying the active length of the filter strip section, thereby permitting tuning to a desired resonant frequency. In addition, tuning of a filter strip section may also be effected by varying its characteristic impedance, thereby varying its effective electric length. This may be readily accomplished (in accordance with theory more fully described hereinafter) by varying the effective spacing between conductive ground planes.

It will be understood that a filter or frequency-selective circuit passes or accepts certain frequencies and rejects

other frequencies, and in many cases the rejection band is as important as the acceptance band. Often, so-called "trap" circuits are employed to reject certain frequency bands and, when used, such rejection bands are considered in this specification to be in the operating range of the filter or frequency-selective circuit. While various arrangements can be employed for supporting the conductive strips between the conductive ground planes, they can be conveniently supported on a thin insulating or dielectric sheet, and advantageously are formed in pairs on opposite sides of the insulating sheet, as described in the aforementioned application.

Coupling between filter sections and from filter sections to input and output sections can be either conductive or non-conductive, as meets the requirements of a particular application. If conductive, the coupling can be altered by merely changing the position at which the coupling strip section contacts the elongated edge of the filter strip section. This change of position varies the impedance presented to the coupling strip and is conveniently used to effect changes in the coupling impedance. If non-conductive, the coupling may additionally be altered by changing the spacing between coupling and filter strip sections.

When the conductive strips are carried by a thin dielectric sheet, it will be understood that techniques such as printing, etching, stamping, etc., can readily be used. Relatively complicated filter structures can be made by merely disposing the conductive strips on a plane surface in the proper configuration, and subsequently inserting the surface between a pair of spaced parallel conductive surfaces. The filter can readily be connected to a coaxial line by means of very simple transitions.

In designing a filter for a particular application, the designer may be guided by conventional filter theory applicable to tuned circuits in selecting the number of tuned circuits required, the degree of coupling between tuned circuits and to input and output circuits, loading, impedance matching, etc.

The invention will be more fully understood by reference to the drawings, which illustrate a number of specific embodiments thereof, taken in conjunction with the following description in which the advantageous features thereof will in part be pointed out and in part be obvious.

In the drawings:

Fig. 1 is a side view partially in cross-section, illustrating a simple form of filter arranged for connection in a coaxial line;

Fig. 2 is a plan view of the filter of Fig. 1 with most of the top plane removed;

Fig. 3 is a sectional view looking toward the side of the element 18 of Figs. 1 and 2;

Fig. 4 is a perspective view of a plurality of coupled short-circuited filter sections, using conductive coupling;

Fig. 4a is a modification of the filter arrangement of Fig. 4 in which the conductive coupling strips are positioned at an angle to the coupled filter sections;

Fig. 5 is a perspective view of coupled shortcircuited filter sections using non-conductive coupling and mounted in a different manner;

Fig. 6 is a perspective view illustrating a movable means for tuning a filter section;

Fig. 7 is a partial side view of Fig. 6 showing the open ends of the tuning members;

Fig. 8 is a plan view of a device for moving the tuning members illustrated in Fig. 6;

Fig. 9 is a side view of the device illustrated in Fig. 8;

Fig. 10 is a perspective view of another means for tuning a filter section;

Fig. 11 is a side view of a device for moving the tuning means illustrated in Fig. 10;

Fig. 12 shows details of the central strip configuration of a specific embodiment of the invention;

Fig. 13 shows a curve applicable to the embodiment of Fig. 12;

Fig. 14 shows details of the central strip configuration of a specific embodiment of the invention used as a portion of the radio frequency circuit for a microwave receiver; and

Figs. 15a and 15b show the use of curved filter strips for particular purposes.

Referring to Figs. 1, 2 and 3, extended conductive plates or sheets 15, 15' are arranged in spaced parallel planes and maintained at a common potential to form ground planes. As specifically shown, the conductive sheets are connected together at spaced points by conductive posts 16, but other means can be employed as meets the convenience of a particular application. Usually sheets 15, 15' will be held at ground potential, but even if held at some other potential, it will be understood that they may be considered as ground planes with respect to the elements therebetween.

Pairs of conductive strips 17, 17', 18, 18' and 19, 19' are fixed to opposite sides of a sheet of low-loss insulating material 21, the lower strip of each pair being exactly the same as the upper strip of that pair and aligned therewith. Insulating sheet 21 is held midway between conductive sheets 15, 15' by suitable means, here shown as posts 16 and short cylindrical spacers 22, 22'.

Strip 18 is a quarter-wavelength long, and is electrically shorted at one end thereof to conductive sheet 15 by means of conductive shorting member 20, and strip 18' is electrically shorted at the corresponding end thereof to conductive strip 15' by means of conductive shorting member 20'.

Strips 17, 17' will here be assumed to be the input section of the transmission line and are, in this embodiment, coupled to a coaxial cable 23 comprising an inner conductor 24 and outer conductor 25. The inner conductor 24 is split at its end to extend over the ends of conductive strips 17, 17' so that the latter are fed in parallel. The outer conductor 25 is connected to conductive sheets 15, 15'. The output section of the transmission line, here assumed to be 19, 19', is similarly connected to a coaxial cable 26. If desired, coaxial cable sections 23 and 26 may be threaded coaxial connectors of known type, so as to permit convenient insertion in a coaxial transmission line.

In operation, the distribution of potential along each strip of a pair should be the same, so that the instantaneous potential of the paired strips is the same at each cross-section. With the input and output ends of the strips connected together as shown, and strips 18, 18' shorted at directly opposed points 27, 27' which are equidistant from the open ends 29, 29' (Fig. 3), ordinarily no further steps need be taken to insure identical distributions. However, if desired, each pair of strips may be connected together at various points along their length by means of conductive eyelets, as explained in the aforementioned application.

Since paired strips function like a single conducting strip, they are included in the term "strip section" as used herein.

Because each pair of strips have the same distribution of potential therealong at any instant, there will be no lines of force between the strips of a given pair and, hence, losses introduced by the presence of insulating material 21 therebetween are very small or negligible. Also, since the space between the conductive strips and the conductive surfaces is free of solid dielectric, the dielectric losses therebetween are very small. Because of these low losses the strip sections are high Q elements.

Such a transmission line is commonly termed an "air-dielectric" line, since dry air usually fills the space. However, for some applications it may be desirable to evacuate the line, or to use some other gaseous medium, and it will be understood that the term "air-dielectric" as used herein includes such cases.

In accordance with the invention, the quarter-wave filter section 18, 18' is coupled between the input and output strip sections. As here shown, the input and output strip sections conductively couple into the sides of the elongated filter strip section within the active length of said element, that is, between the shorted end and the open end thereof. The elongated filter section has a resonant length from shorted end to open end equal to an odd multiple of quarter-wavelengths at the operating frequency thereof. Usually one-quarter-wavelength elements suffice and are advantageous from the standpoint of size. It will be understood that "active length" of a resonant element as used herein refers to the length of an element actually participating in the filtering function.

In accordance with accepted theory, the standing voltage wave on a shorted quarter-wavelength element is sinusoidal varying from approximately zero on the shorted end to a maximum at the open end. On the other hand, the corresponding current wave is approximately zero at the open end and a maximum at the shorted end. It will be noted that the open ends 29, 29' of the elongated strip sections 18, 18' terminate at the edge of insulating strip 21. It is desirable to design the filter in this manner in order to avoid dielectric losses in strip 21 due to the fields created by the high voltages at the open ends of the shorted quarter-wavelength elements. If additional loss reduction is required, the insulating sheet may be cut away about the edges of the resonant element near the open end.

Due to the standing voltage and current waves along the length of the quarter-wavelength element, variations of the position of the input and output conductive strip sections on the elongated sides of filter strip sections 18, 18' will vary the impedance presented to the input and output sections.

Because of the variation of impedance along the filter strip section, the input and output sections may be positioned relative to one another along the opposite elongated sides of section 18, 18' to effect an impedance transformation therebetween, the junctions between the input and output sections and the filter section acting in effect as a transformer which may either step up or step down the impedance depending upon the contact positions along the sides of the filter section.

As has been mentioned hereinbefore, symmetrical strip line has very low losses, and therefore the Q of a filter strip section formed therefrom is very high. Filter section 18, 18', therefore, functions substantially as a single tuned resonant circuit with a very high Q. Consequently, it is possible to obtain a very narrow pass band for the arrangement shown in Fig. 1. The coupling may be varied in the manner indicated and to a degree in accordance with well-known filter theory, to meet various requirements of band width and attenuation.

Filter strip section 18, 18' is preferably disposed perpendicular to the immediately adjacent portions of the input and output conductive strip sections in order to avoid spurious couplings, although this is not always necessary and may be departed from if desired for a particular application.

It is pertinent to note at this point various relationships of strip line parameters that are helpful in the design of a filter formed from such units.

The characteristic impedance of strip line section varies with the ratio between the width of the strip section and the spacing of the ground planes. As the ratio becomes greater, the characteristic impedance decreases. The thickness of the central conductive strip (or the separation of the strips by the insulating sheet in the case of paired strips) also has an effect on the characteristic impedance, greater ratios between thickness and separation of ground planes yielding lower impedances. It is, therefore, possible to vary coupling and impedance effects between strip sections by varying the parameters mentioned above on one strip section relative to another.

In the design of filter sections it is important to recognize the factors which affect the unloaded Q thereof. The unloaded Q varies with the impedance of the strip transmission line. Therefore, increased width will increase the unloaded Q of any such section. In general it is desirable to keep the impedance of the strip transmission line low in order to minimize losses. In addition, it has been experimentally determined that if other parameters are adjusted to maintain a given characteristic impedance, the unloaded Q increases significantly as the spacing between ground planes is increased. To avoid spurious responses, however, it is usually desirable to limit the width of each resonant strip, and also the separation of the ground planes 15, 15' so that higher modes are not excited. While not always essential, making the separation of the ground planes 15, 15' less than a half-wavelength has been found desirable in practice. Also, although theory indicates a slightly more lenient condition, it is found advantageous to select the width of the resonant strips so that the sum of the width of the strip plus the spacing between ground planes is also less than a half-wavelength of the energy to be transmitted.

Many modifications in the arrangement of Figs. 1, 2 and 3 are possible, and a few may be stated here. Instead of using pairs of strips, only a single strip on one side of the insulating sheet 21 may be employed in each section, in which case it is advantageous to mount the sheet 21 slightly off-center so that the conductive strip will be substantially equidistant from the ground planes. While exact centering is desirable, some tolerance is allowable without seriously degrading performance. The input and output sections have been shown quite long, and insure that these sections will be substantially electrically flat. However, they may be made quite short in many cases. While it is possible to couple the resonant section directly to coaxial line sections, it is preferred to employ at least short sections of strip transmission line adjacent the resonant section.

Instead of using conductive posts 16 to join the ground planes, it is often convenient to employ solid side plates integral with one sheet, say 15', and arrange the other sheet 15 as a cover to be secured in place after the sheet 21 and associated conductive strips have been put in place.

Even when the sides are open, the lateral extent of ground planes 15, 15' prevents significant radiation of energy in a lateral direction from the transmission lines 17, 17' and 19, 19', thus preventing interference with adjacent lines and vice versa. For ground plane spacings less than a half-wavelength, the transverse fields are attenuated as in a waveguide beyond cutoff and conventional waveguide formulas can be employed, particularly those for the TM_{11} mode. Generally, the transverse spacing between different lines should be at least equal to the ground plane spacing to avoid coupling therebetween, and greater spacing will further decrease the coupling.

An additional consideration is the avoidance of radiation from filter section 18, 18'. An extension to the ground planes beyond the open end of said section by at least the width of said section is suggested. If the thickness of the shorting member 20, 20' is substantially greater than the width of filter section 18, 18', the ground planes can terminate along the outer boundary of said member as indicated in Fig. 3, providing the extension of the ground planes is sufficient to avoid lateral radiation from input and output sections 17, 17' and 19, 19'.

Fig. 4 illustrates a multiple section filter using paired strip construction, the top layer of which is composed of three resonant filter strip sections comprising elongated strips 41, 42, 43, coupling strips 44 and 45, conductive shorting strip 46, shorting member 48 and input and output sections 47 and 49. The filter strip sections

are conductively coupled together by coupling strips 44, 45. At one extreme of their active lengths they are tied together by shorting strip 46. (Fig. 4a clearly illustrates this feature.) Shorting member 48 conductively shorts the elongated strip filter sections to ground plane 15. Input and output sections, here assumed to be 47 and 49, respectively, conductively couple into and out of the filter.

On the opposite surface of insulating sheet 21 an identical configuration is presented in accordance with the construction previously described, and is shorted to conductive surface 15' by means of shorting member 48'. Future discussions of configurations using this symmetrical paired construction will refer only to the top layer of strip sections.

The various constructional details illustrated in Figs. 1, 2 and 3 discussed above are omitted in Fig. 4 and the subsequent figures, but will be understood to apply throughout. For simplicity, only the arrangement of conductive strips and their functioning will be described.

The particular configuration used in Fig. 4 controls the transmission of microwave energy over a relatively broad but well-defined frequency range and is generally equivalent to an ordinary band pass filter using tuned resonant circuits. In this embodiment of the invention, the shorted quarter-wavelength filter sections are of equal active length and, therefore, are tuned to the same resonant frequency. Some lateral non-conductive coupling exists between the resonant elements due to the relatively close spacing thereof, but may be avoided if desired by increasing the spacing between adjacent sides. The position of coupling strips 44 and 45 along the sides of the coupled resonant strip sections affects the coupling between resonant sections, as has been indicated before. Since several coupled resonant filter sections are generally equivalent to a corresponding number of coupled tuned resonant circuits with lumped components, changes in the coupling between the sections will affect the band pass characteristic in much the same manner as in lumped circuitry. Therefore, the band pass characteristic of the multi-element filter may be altered by locating the coupling strips 44 and 45 closer to or further away from the shorting member 48.

Impedance changes between strip sections can also be effected if desired. Since coupling strips 44 and 45 are perpendicular to the parallel filter strip sections, each will contact the sections it couples together at points of like impedance. If the coupling strip section is short in length, its impedance may be neglected. If not, and it is desirable to obtain an impedance match, the coupling strips 44 and 45 may be angled between resonant sections to compensate for their own impedance as illustrated in Fig. 4a. It is desirable that coupling strip sections be relatively short compared to a resonant strip so that they will be non-resonant at the operating frequencies. As has been mentioned before, impedance transformations or matching between input and output sections can also be effected by changing the position of the input and output sections 47 and 49 along the sides of the filter sections to which they are coupled.

As will be understood by those skilled in the art, the physical length of a resonant strip section such as 41 will not be exactly an odd multiple of a quarter-wavelength at the resonant frequency due to fringe effects and coupling to adjacent elements. Those skilled in the art will also realize that the lengths of the resonant strips may be made different so that they resonate at different frequencies, thereby altering the frequency characteristic to suit a particular purpose.

Fig. 5 illustrates a different construction and coupling technique within the scope of the invention.

In this embodiment, the strip sections are solid and not of the paired construction indicated in the preceding figures. Conductive strips 57 and 59 forming input and output sections are supported midway between ground

planes 15, 15' by insulating blocks 52, 52' made of low-loss material to hold dielectric losses to a minimum. For example, material known as "Polyfoam" has been employed with success. Since the input and output are essentially non-resonant, supports 52, 52' are advantageously spaced at odd multiples of a quarter-wavelength apart at the operating frequency, although other spacings may be employed if desired. The shorted ends of filter sections 54 and 55 are embedded in a solid shorting block 51 providing an electrical short-circuit to ground planes 15, 15' and also support.

Fig. 5 also illustrates non-conductive coupling techniques that may be used if desired for a particular application. Coupling between the input conductive strip section 57 and filter strip section 54 is capacitive, as is the coupling between output section 59 and filter section 55. This coupling may be varied by changing the spacing between adjacent sections.

As has been mentioned before, lateral coupling exists between adjacent filter strip sections if they are not sufficiently spaced from one another. This factor may be used to advantage if desired by spacing the adjacent filter sections closely together to obtain appropriate coupling without the necessity of using intervening coupling strip sections. It is also possible to obtain non-conductive coupling between adjacent filter strip sections by using an intervening coupling strip whose ends are closely spaced from the sides of the pair of resonant strip sections but insulated therefrom, thereby capacitively coupling the two. It is evident that any combination of the non-conductive and conductive coupling techniques described may be used for a particular application.

Particular filter configurations have been described to indicate the variety of filter circuits possible. It is evident that all of the described embodiments may be combined in whole or in part to effect a desired filtering action.

In many applications a tunable filter is required, and in such cases the active length of a filter strip section may be varied in order to change the resonant frequency thereof. This may be accomplished by moving the shorting member of the filter section toward or away from the open end of said section. It is possible to move the shorting member 20 illustrated in Fig. 1 by adapting it to bear against the filter section and ground plane while being permitted to slide over the desired length range.

To avoid sliding contacts, a pair of non-contacting plungers may be used as illustrated in Figs. 6 and 7. The active length of filter strip section 78 is to be made variable over a certain desired range. Therefore, the distance between open end 75 to the point of short circuit of the filter strip section must be made variable over the desired range. The point of short circuit of the filter strip section 78 is approximately directly below surface 76 of plunger 71, and the plunger is arranged to be movable over the desired range. In order to obtain proper shorting of filter element 78, it should extend from the grounding point to or beyond the open end of the plunger 71 when the plunger is at its most extreme tuning position, that is, when the active length of filter section 78 is greatest. Input and output conductive strip sections 17 and 19 conductively couple into elongated section 78 at points which are within the active length of said element.

Non-contacting plungers 71 and 71' are identical and are disposed one between each ground plane and its opposing filter strip section surface. The preferred construction of plunger 71 includes two conductive planar sections 72 and 73 parallel to each other, the ground planes, and the filter section, disposed directly above one another. They are closely spaced to the adjacent surfaces. Conductive shorting link 74 is perpendicular to both planar sections and short-circuits them together.

at one extreme. The length of planar sections 72 and 73 from the surface 76 of connecting link 74 is preferably an odd integral multiple of quarter-wavelengths at the center frequency of the frequency range through which filter section 78 is to be tuned. Plunger 71 preferably extends in width beyond either side of filter section 78 by approximately the width of said filter section or more. The construction of plunger 71' is identical to that of plunger 71.

The operation of plunger 71 may be explained as follows. Shorting section 74 short-circuits the closed end of the plunger and, since the plunger is a quarter-wavelength long (or odd multiple thereof), establishes an effective open circuit at the open end thereof. Consequently no current can flow between strip 78 and ground plane 15 at the open end of plunger 71, thereby establishing an effective open circuit at this point. Hence, by the quarter-wavelength relationship, an effective short-circuit is established between strip 78 and ground plane 15 in the region of section 74, and approximately at the surface 76.

It is not necessary that there be exact coincidence between the shorting point and surface 76 since the plunger can be moved to compensate for any inaccuracies. The range of resonant frequency variation is limited by the departure of the plungers from a perfect short circuit as the selected frequency departs from that for which the effective electrical length of the planar sections 72 and 73 is an odd multiple of quarter-wavelengths. For high Q applications where the non-contacting plungers must present substantially zero impedance from filter section to ground plane, this motion may be limited to a small fraction of a wavelength, but is nevertheless sufficient for many applications.

Figs. 8 and 9 illustrate a cam mechanism which may be employed for imparting controlled motion to plungers 71, 71'. Ground plane 15 supports a shaft 81 to which is sweated a cam 82. Cam 82 bears against bar 83 and is held in positive contact therewith by a pair of springs 84. Springs 84 are anchored to posts 85 which are supported by ground planes 15 and 15' and connected to rod 86 on the plunger assembly.

Bar 83 and rod 86 are bolted to side plates 87 which are constructed of low loss phenolic dielectric material. Non-contacting plungers 71, 71' are attached to and supported by these side plates 87. Teflon buttons 88 are also cemented to non-contacting plungers 71, 71' and serve to support the complete structure between ground planes 15, 15'.

By rotating shaft 81, plungers 71, 71' may be moved along the filter strip section 78, thereby changing its active length which extends a quarter of a wavelength or an odd multiple thereof beyond the plungers at the resonant frequency thereof.

The eccentricity of cam 82 determines the maximum motion that can be imparted to plungers 71, 71'. The cam mechanism illustrated here is quite capable of producing as much motion as is electrically tolerable because of the limitation mentioned before.

Rather than move the short circuit, it is sometimes more convenient to change the effective electrical length of a resonant filter strip section by changing its characteristic impedance. If the characteristic impedance of the open end portion of the resonant strip is changed, the resonant frequency also changes. As has been described before, the characteristic impedance of a strip section varies with the ratio of its width to the spacing between ground planes. Changing the spacing between ground planes will therefore vary the characteristic impedance, other parameters remaining the same. If this is effected at the open end of the resonant strip, a change in resonant frequency results.

Fig. 10 illustrates an embodiment of this feature of the invention which symmetrically changes the spacing of

the ground planes near the open end of the shorted filter strip section shown.

Conductive planar sections 103 and 104 bear against the inner surfaces of ground planes 15, 15' and make electrical contact therewith, thereby functioning as ground planes of closer spacing. Connecting link 102 is utilized to move both planar sections simultaneously and does not necessarily have to be conductive. Planar sections 103 and 104 are located above and below elongated strips 18 and 18'. With the sections 103, 104 completely withdrawn, the resonant strip functions as described hereinbefore. As they are moved forward to overlap the ends of strips 18, 18', the characteristic impedance of the overlapped section is lowered, thus changing the resonant frequency of the strip.

Since most of the field from the elongated strip 18, 18' to the ground planes is limited to the width of the strip, most of the tuning effect is produced by that portion of the tuning member which directly overlaps the strip. When tuning member 101 must occupy minimum space, it is sufficient for it to be as wide as the strips 18, 18', or even narrower if only a trimming action is desired. However, when space permits, it is desirable to have sections 103, 104 extend beyond the sides of strips 18, 18' by the width of the strips or more.

The characteristic impedance may also be changed by using a dielectric material for sections 103, 104 rather than a metal, although such an embodiment introduces dielectric losses which are usually undesirable.

Fig. 11 shows a simple means for imparting motion to tuning element 101. The two ground planes 15, 15' are spaced one from the other in the manner illustrated in Fig. 1, with the addition of posts 111 and spacers 112. A resonant filter strip section 18, 18' is supported on a wide dielectric sheet 21. The movable insert 101 is driven by a threaded shaft 113 affixed thereto and passing through holes in metal support blocks 114. These blocks also serve to support and space the ground planes relative to one another and are fastened thereto by posts 115. A threaded thumb screw 116 on threaded shaft 113 is mounted between the support blocks and thereby restrained from axial movement. Apertures in the ground plane allow the thumb screw to project therethrough to give access for tuning.

Because of these apertures in the ground planes and the metal structure in the metal portions of the drive mechanism, the mechanism is preferably supported at a distance from the end of the filter strip section 18, 18' which is several times the spacing between the ground planes 15, 15'. The greater the separation, the less the effect of the tuning structure on the electrical characteristics of the filter section. In operation, the thumb screw is rotated to drive the tuning member into or out of the field in the vicinity of the end of the resonant filter strip section.

Specific examples of filters embodying features already described, but designed for particular applications, together with a curve applicable to one embodiment will now be given.

In Fig. 12 a filter utilizing three filter strip sections is shown. A thin sheet 121 of a high-grade insulating material composed of fiber glass bonded with Teflon is laminated with sheets of copper of foil thickness on each side thereof, and is employed as the central section. The foil is removed on both sides of the insulating sheet except in the areas shown in Fig. 12. The strip arrangement shown is similar to that shown in perspective in Fig. 4. The three parallel resonant filter strip sections are interposed between input and output lines 125 and 126. The insulating sheet is supported midway between two extended ground planes (not shown) which are spaced three-eighths of an inch apart. Shorting strip section 127 connects the three resonant sections together at their shorted ends and a shorting member (not shown) connects them to the ground planes. The input and output

sections 125 and 126 are disposed parallel to the resonant sections along a considerable portion of their length so as to effect an economy of space. It should be noted that there is little lateral coupling between the input and output sections and adjacent resonant strip sections because the input and output sections are non-resonant. The lateral coupling between two high Q resonant sections is much greater for identical spacing.

The ends of input and output strip sections 130 and 131 are tapered in order to provide a more perfect match with the coaxial lines connected thereto. The connection of coaxial lines is illustrated in Fig. 1. The tapered arrangement of Fig. 12 is preferred to squared end configuration of Fig. 1, although the latter may be employed if desired. The ends of input and output conductive strip sections 125 and 126 which couple into filter sections 122 and 124, respectively, are tapered in order to decrease the impedance spread contacted by the input and output strip sections. Theoretically point contact would appear to be best, but in practice it is not found essential. However, preferably the length of contact should be kept fairly small.

Since the positions of the input and output sections 125, 126 along the sides of filter strip sections 122, 124 determine the degree of coupling and impedance match, they also determine the loading of the filter and hence the amplitude of the peaks and valleys within the pass band characteristic. The points of coupling between filter strip sections determined by the positions of coupling strips 128 and 129 largely control the band width.

In order to tune the filter after construction, slight changes in the length of the filter sections may be required. This can be effected by trimming the filter strip sections to reduce their lengths slightly, or adding a little solder to increase the length.

The performance of the filter of Fig. 12 is shown in Fig. 13, where the response in terms of db is plotted against frequency in kilomegacycles.

Fig. 14 illustrates a filter arrangement which is used as a portion of the radio frequency circuit for a microwave receiver. The configuration of the center conductor of the circuit is shown, the constructional details being similar to those of Fig. 12. Ground planes (not shown) overlap both surfaces.

Signal energy is fed into a four-section filter through a strip transmission section 141 which feeds into an impedance matching section 142 of somewhat narrower width to present a characteristic impedance which is the geometric mean between the impedance of the incoming transmission line 141 and the impedance of the point along the side of the first filter section 143 at which strip 142 conductively couples to said filter section. The four filter sections 143, 144, 145 and 146 of the filter are connected to the shorting member through a continuous strip 147 along their shorted ends, and are conductively coupled to one another by narrow coupling strips 148, 149 and 150. Energy is coupled out of the four-section filter conductively to a small tab 150.

Local oscillator energy is supplied to a single filter section 152 shorted to the ground planes by means of strip 153. Filter section 152 is capacitively coupled through 151 to tab 150. The local oscillator energy is fed to filter section 152 through a conductive feed soldered thereto (not shown in the drawing).

Tab 150 therefore receives the signal frequency from the four-section filter and the local oscillator frequency from the single section filter. The two frequencies are conductively supplied to a mixer crystal 154.

The reactance of the crystal is reflected into filter section 146 and affects the frequency thereof. In order to make the resonant frequency of filter section 146 equal to that of sections 145, 144 and 143, section 146 is made shorter than the others to tune out this reactance. The insulating sheet is notched near the active ends of all

the resonant filter elements to accept a tuning member such as that illustrated in Fig. 10.

Probe element 155 capacitively couples a small portion of energy from the filter and is used to initially align said filter. The alignment is effected by first shorting the open end of filter section 144 and then tuning filter section 143 to a maximum at the desired resonant frequency by either shortening or lengthening said strip section. The short is then removed from filter section 144 and is moved to the open end of filter section 145. Since the adjacent coupled filter sections are electrically a quarter-wavelength apart, filter section 144 is now tuned so that the energy coupled into probe 155 is at a minimum, thereby indicating a voltage maximum at filter section 144. This procedure is continued until all the four filter sections are tuned to the selected resonant frequency.

In all the preceding specific embodiments the resonant strip sections are straight, and the input and output lines are either straight or have right angle bends therein. This ordinarily facilitates construction. However, it is not essential. For example, the resonant strip elements can be curved, the input and output lines can be curved, or other than right angle bends can be employed.

For some applications, curvature of adjacent coupled resonant strip elements can be employed to obtain a desired variation in bandwidth with frequency in tunable circuits. As has been explained in connection with Fig. 4, if adjacent resonant strip elements are sufficiently close, some coupling exists between the strip elements themselves in addition to the coupling provided by the coupling strips therebetween. In Fig. 5 the entire coupling between the two resonant strip sections is obtained in this manner. Such coupling is a combination of capacitive and inductive coupling. Near the grounded ends of the resonant strip elements (e.g. 54, 55 in Fig. 5) the coupling is predominantly inductive. Near the open ends the coupling is predominantly capacitive. If such a filter is arranged to be tunable, as described in connection with Figs. 6 and 10, a certain relationship between bandwidth and frequency is obtained as the filter is tuned over a range of frequencies.

In some cases it is desired to obtain a different type of bandwidth variation with frequency from that obtainable with the coupling arrangements shown in Figs. 4 and 5, for example.

Figs. 15a and 15b illustrate arrangements useful in such situations. Fig. 15a illustrates a central strip configuration which will be understood to be supported midway between ground planes, as shown in previous embodiments. Resonant filter strip elements 161 and 162 are connected at their grounded ends by conductive strip 163, which will be understood to be shorted to the ground planes, as illustrated in previous figures. Input and output transmission lines 164 and 165 are shown conductively coupled to the resonant elements, but can be reactively coupled thereto if desired.

The grounded ends 161' and 162' are relatively close together, and the spacing is such that the desired amount of coupling (predominantly inductive) exists. Due to the curvature, the outer ends 161'' and 162'' are much farther apart so as to reduce the coupling therebetween (predominantly capacitive). By virtue of this arrangement the entire coupling between the two resonant strip elements is predominantly inductive. If, then, the filter is arranged to be tunable, as described in connection with Fig. 10, or as described in connection with Fig. 6 by removing the ground section 163 and extending the strip elements, the percent bandwidth remains substantially constant as the frequency varies. This is often a desired relationship for particular applications. The arrangement can, of course, be combined with additional filter sections composed of straight resonant elements to obtain particular results.

When input and output lines 164 and 165 are capacitively coupled to the resonant elements, as described for

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example in connection with Fig. 5, the point of coupling between one transmission line and the corresponding resonant element can be moved along the resonant element even to the open end thereof to obtain particular characteristics. This is also true of the embodiment shown in Fig. 5.

Fig. 15b illustrates a different curved arrangement in which the grounded ends of the resonant strips are far apart and the open ends are close together. In this arrangement the coupling between the resonant strips is predominantly capacitive. If, then, the filter is tuned, as described hereinbefore, the percent bandwidth increases with frequency. While this arrangement is in general not as useful as that shown in Fig. 15a, it may be helpful in specific cases.

In both Figs. 15a and 15b additional coupling between the resonant strips may be employed to modify the bandwidth variation with frequency.

As pointed out hereinbefore, it is preferred to employ matching or paired strips on opposite sides of a thin sheet of insulating material for the central conductor of the input and output section and filter sections, since very little loss and resultant high Q's are obtained. When desired, strips on only one side may be employed, and since the insulating sheet may be very thin the dielectric between conductive strip and ground planes is substantially air-dielectric.

There are now available foamed polystyrene ("Polyfoam") and foamed vinyl chloride. In these materials, a very large percentage of the volume is air, and only a very small percentage is solid dielectric. Hence they may be termed essentially air-dielectric materials, and are usable to support the conductive strip sections between the ground planes. While localizing the support members is preferred, as illustrated in Fig. 5, for some purposes this is not necessary. Similar blown up, expanded or sponge-like materials whose volume is largely air may also be employed in some applications.

The frequency-selective circuits of the invention find particular usefulness at frequencies above 1000 megacycles, and become smaller and more compact as the frequency increases. In the region from 5000 to 10,000 megacycles and upwards they are particularly valuable since comparable coaxial line and waveguide arrangements become very expensive even if practical to design. They may, however, be used at somewhat lower frequencies if the physical size is not a drawback. It will be understood that the term "microwave" as used herein includes these frequency ranges.

The specific embodiments described herein are in the class known as four-terminal networks, having separate input and output pairs of terminals. When more than one resonant section is interposed between input and output sections, it will be understood that a given resonant section serves as a coupling between another resonant section and the input or output line. For some purposes a two-terminal frequency-selective circuit suffices, and it will be understood that the arrangements of the present invention are usable in this manner.

A number of different embodiments of the invention have been described to illustrate the versatility thereof. Various combinations of the features described in different embodiments are, of course, possible, and may be selected to meet the requirement of the particular application. Also, filters designed in accordance with the present invention can be combined with those described in application Serial No. 469,454, above mentioned.

I claim:

1. A microwave frequency-selective circuit which comprises a pair of conductive surfaces in spaced parallel planes maintained at a common potential to form ground planes, a circuit element resonant within the operating range of said frequency-selective circuit comprising an elongated conductive strip section supported midway between said conductive surfaces in parallel spaced rela-

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tionship therewith and a shorting member adapted to electrically short-circuit the elongated section to the conductive surfaces at a point along the length thereof, tuning means movable between at least a portion of said elongated section and said conductive surfaces to change the characteristic impedance of said portion and thereby change the effective electrical length of said elongated section over a desired range, each effective electrical length within said range being substantially an odd integral multiple of quarter-wavelengths at the resonant frequency of the elongated section, and microwave transmission line means coupled to said elongated section including a conductive strip section supported midway between said conductive surfaces in parallel relationship therewith.

2. A microwave frequency-selective circuit which comprises a pair of conductive surfaces in spaced parallel planes maintained at a common potential to form ground planes, a circuit element resonant within the operating range of said frequency-selective circuit comprising an elongated conductive strip section supported midway between said conductive surfaces in spaced parallel relationship therewith and a pair of movable conductive shorting members adapted to electrically short-circuit the elongated section to the conductive surfaces over a range of positions from the open end thereof comprising the tuning range of said shorting members, said shorting members being movable simultaneously between said elongated section and said conductive surfaces, respectively, and insulated therefrom, each shorting member comprising a pair of planar conductive sections in spaced relationship parallel to each other and parallel to the conductive surfaces and a conductive link connecting said planar sections together, said planar sections extending from said connecting link away from the open end of said elongated section, said elongated section having a length sufficient to extend beneath substantially the entire length of the adjacent planar sections of said movable shorting members when the conductive links of said shorting members are positioned at their extreme tuning position from the open end of said elongated section, the distance from any position of the connecting links within the tuning range of the shorting members to the open end of the elongated section being approximately an odd integral multiple of quarter-wavelengths at the resonant frequency of said elongated section, the planar sections of each shorting member extending from the connecting link to the open end thereof approximately an odd integral multiple of quarter-wavelengths at a selected resonant frequency within the frequency range of the elongated section, the active length of said elongated section and said conductive surfaces having substantially air-dielectric therebetween, and microwave transmission line means coupled to said elongated section including a conductive strip section supported midway between said conductive surfaces in parallel relationship therewith.

3. A microwave frequency-selective circuit in accordance with claim 2 in which the planar sections and connecting link of each shorting member extend beyond the sides of the elongated section at least approximately the width of said elongated section.

4. A microwave frequency-selective circuit which comprises a pair of conductive surfaces in spaced parallel planes maintained at a common potential to form ground planes, a circuit element resonant within the operating range of said frequency-selective circuit comprising an elongated conductive strip section supported midway between said conductive surfaces in spaced parallel relationship therewith and a shorting member adapted to electrically short-circuit the elongated section to the conductive surfaces at a point remote from the open end thereof, a tuning member having a pair of insert sections positioned between each conductive surface and said elongated section respectively and insulated from the

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elongated section, said insert sections being movable simultaneously between said elongated section and the conductive surfaces from the open end of the elongated section, the effective electrical length of said elongated section being substantially an odd integral multiple of quarter-wavelengths at the resonant frequency thereof, the portion of said elongated section between said insert sections and said shorting member being separated from said conductive surfaces by substantially air dielectric, and a microwave transmission line means coupled to said elongated section including a conductive strip section supported midway between said conductive surfaces in parallel relationship therewith.

5. A microwave frequency-selective circuit in accordance with claim 4 in which the insert sections are of dielectric material.

6. A microwave frequency-selective circuit in accordance with claim 4 in which the insert sections are of conductive material and make electrical contact with the said conductive surfaces.

7. A microwave frequency-selective circuit in accordance with claim 4 in which the insert sections are of conductive material and make electrical contact with the said conductive surfaces, each insert section having a surface area opposing the elongated section which is planar and parallel to said elongated section.

8. A microwave frequency-selective circuit in accordance with claim 4 in which the insert sections are planar conductive sections arranged parallel to the elongated section and bear against the conductive surfaces making electrical contact therewith.

9. A microwave frequency-selective circuit which comprises a pair of conductive surfaces in spaced parallel planes maintained at a common potential to form ground planes, a circuit element resonant within the operating range of said frequency-selective circuit comprising an elongated conductive strip section supported midway between said conductive surfaces in parallel relationship therewith and a shorting member adapted to electrically short-circuit the elongated section to the conductive surfaces at a point remote from the open end thereof, a substantially U-shaped tuning member insulated from said elongated section comprising two substantially identical conductive planar insert sections positioned between each ground plane and said elongated section respectively and arranged parallel thereto, each planar section bearing against the respective conductive surface and in electrical contact therewith, and a link connecting said insert sections, said U-shaped tuning member being positioned with its opening directed towards the open end of the elongated section and being movable along the length of the elongated section so that the planar insert sections may be introduced between the elongated section and the conductive surfaces, the active length of the elongated section being such that at any position of the tuning member within its tuning range the effective electrical length of the elongated section is equal to

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an odd multiple of quarter-wavelengths at the resonant frequency thereof, the space between said elongated section and said conductive surfaces and U-shaped member being substantially air-dielectric, and microwave transmission line means coupled to said elongated section including a conductive strip section supported midway between said conductive surfaces in parallel relationship therewith.

10. A microwave frequency-selective circuit which comprises a pair of conductive surfaces in spaced parallel planes maintained at a common potential to form ground planes, a pair of coupled circuit elements resonant within the operating range of said frequency-selective circuit, each of said resonant elements comprising an elongated conductive strip section supported midway between said conductive surfaces in parallel relationship therewith and a shorting member adapted to electrically short-circuit the elongated section to the conductive surfaces at a point remote from the open end thereof, said elongated strip sections being arranged so that the separation therebetween at the grounded ends thereof is substantially different from the separation at the open ends thereof whereby one type of reactive coupling therebetween predominates, movable tuning means for simultaneously changing the effective electrical length of said elongated sections over a desired range, each effective electrical length within said range being equal to an odd integral multiple of quarter-wavelengths at the resonant frequency of the elongated section, and microwave transmission line means coupled to said coupled elongated sections.

11. A microwave frequency-selective circuit in accordance with claim 10 in which the separation between the grounded ends of the elongated strip sections is substantially less than the separation between the open ends thereof.

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