

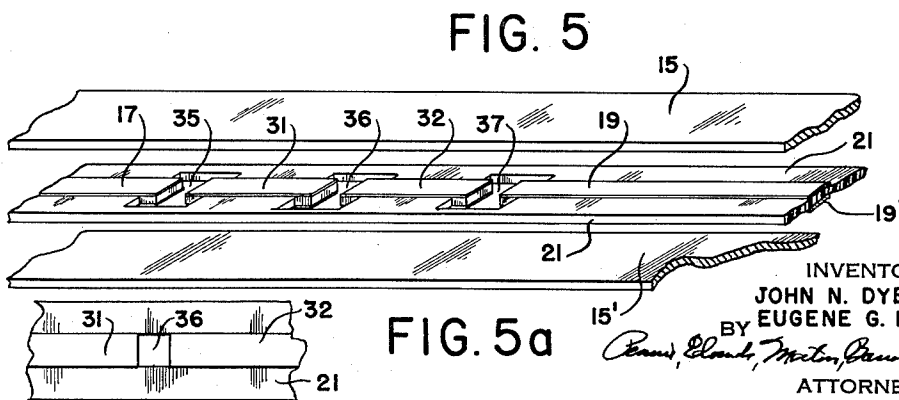
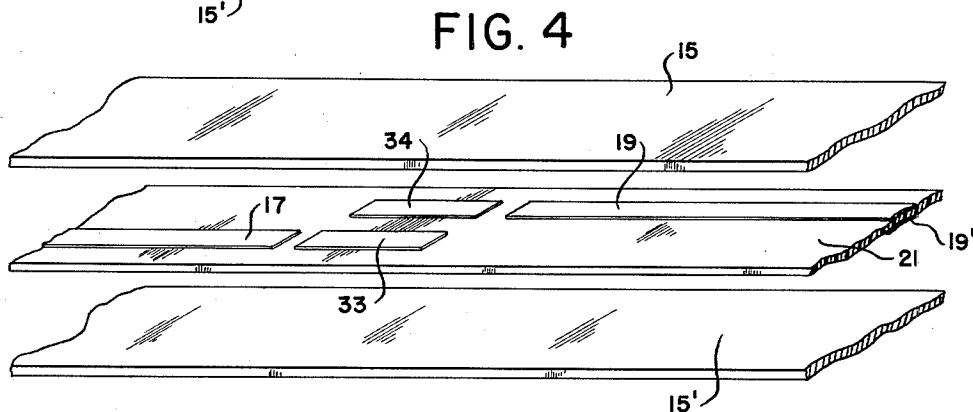
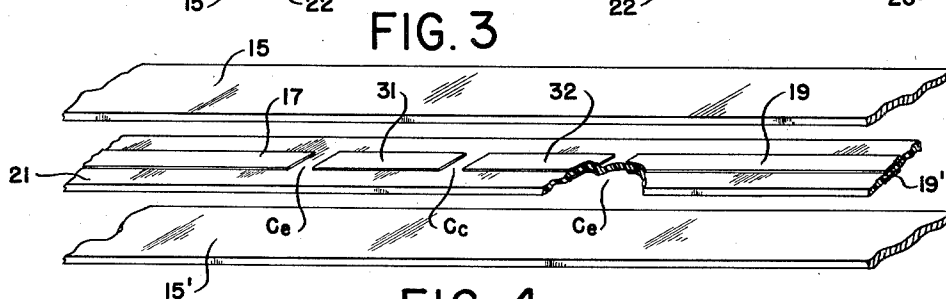
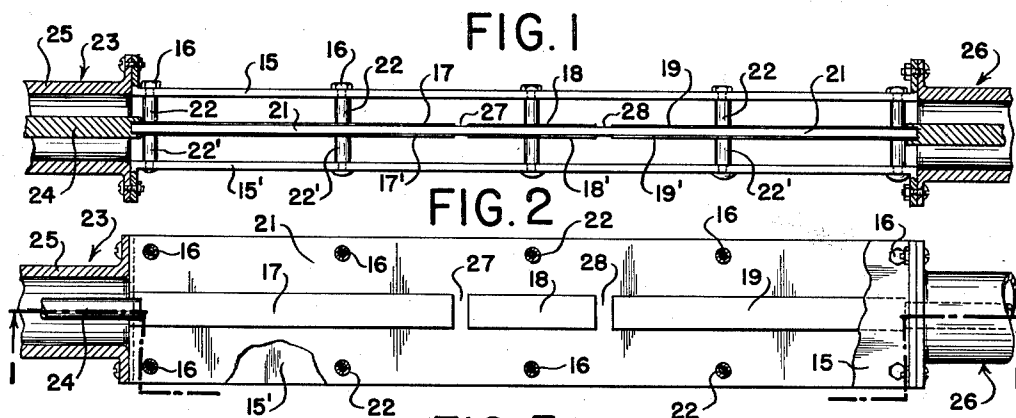
May 16, 1961

J. N. DYER ET AL
MICROWAVE CIRCUITS

2,984,802

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3 Sheets-Sheet 1



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3 Sheets-Sheet 2

FIG. 6

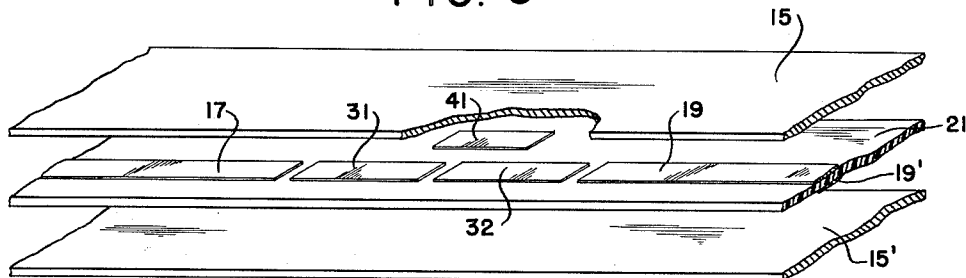


FIG. 7

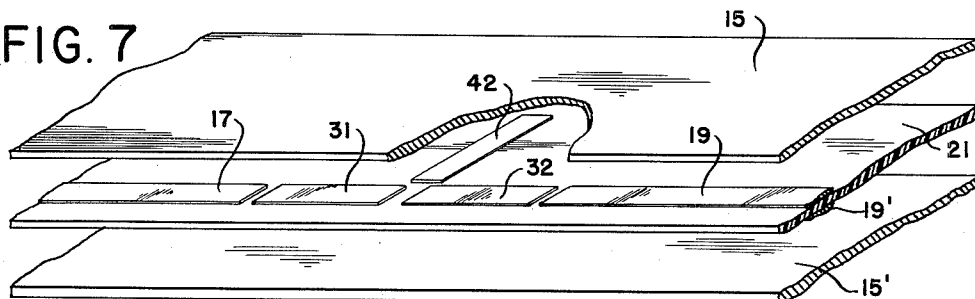
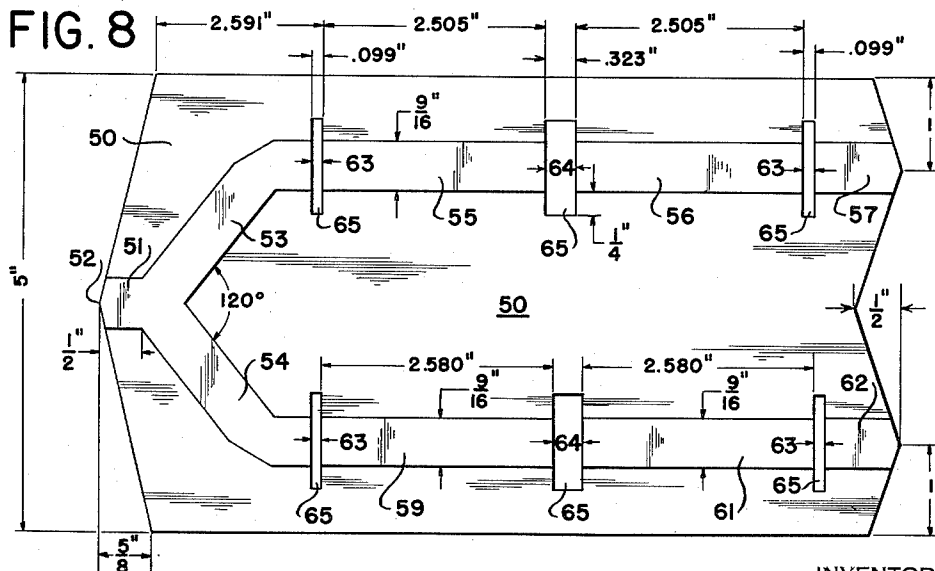


FIG. 8



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1

2,984,802

MICROWAVE CIRCUITS

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2 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.

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 Patent No. 2,913,686, issued November 17, 1959 to Fubini et al. 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.

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

2

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 a primary object of the present invention to provide 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.

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 and insulated therefrom, 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 Patent No. 2,913,686, 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 integral multiple of half-wavelengths at the resonant frequency thereof, it being understood that the term "multiple" includes one. Thus a single resonant strip is generally equivalent to a single tuned L-C resonant circuit having a high Q. When two strips of the same resonant frequency are coupled together, the overall characteristic may be single-humped or double-humped depending on the degree of coupling and the Q of the strips, analogous to two L-C circuits with lumped constants tuned to the same frequency and coupled together.

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 conveniently be 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 conductive or capacitive as meets the requirements of a given application. If capacitive, the coupling can be altered by merely changing the spacing between sections, although other means are also described hereinafter. 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 employed. 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. Impedance matching in the pass band is also relatively simple.

In designing a filter for a particular application, the designer may be guided by conventional filter theory

3

applicable to tuned circuits in selecting the number of tuned circuits required, the use of series or parallel arrangements, 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 plate removed;

Fig. 3 is a perspective view of a filter having a plurality of resonant sections with longitudinal or end-to-end coupling;

Fig. 4 is a perspective view of a filter employing transverse or side-to-side coupling between resonant sections;

Fig. 5 illustrates longitudinally coupled resonant sections in a preferred form of the invention;

Fig. 5a illustrates a modification of the arrangement of Fig. 5;

Fig. 6 is a modification showing additional coupling between resonant sections;

Fig. 7 illustrates the use of a perpendicularly arranged resonant section to serve as a wave trap;

Fig. 8 shows details of a specific embodiment of the invention which has been found satisfactory in use;

Fig. 9 shows curves applicable to the arrangement of Fig. 8;

Fig. 10 illustrates a further embodiment of the invention; and

Fig. 11 illustrates the use of conductive coupling.

Referring now to Figs. 1 and 2, 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 given 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 affixed 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'.

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, say 17 and 17', 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, ordinarily no further steps need be taken to insure identical potential distributions. However, if desired, each pair of strips may be connected together at various points

4

along their length by means of conductive eyelets, as explained in the aforementioned application. Since 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, say 17, 17', and the conductive surfaces 15, 15' is free of solid dielectric, the dielectric losses therebetween are very small.

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 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 filter section 18, 18' is coupled between the input and output sections. As here shown, it is coupled in longitudinal or end-to-end relationship. The filter section is elongated and has a resonant length approximately equal to a multiple of half-wavelengths at the operating frequency thereof. Usually half-wavelength elements suffice, and are advantageous from the standpoint of size. The degree of coupling of filter section 18, 18' with the input and output sections is determined by the width of spaces 27 and 28. The narrower the spaces, the greater the coupling, and vice versa. Filter section 18, 18' functions substantially as a single-tuned resonant circuit and, since symmetrical strip line of the character described has very low losses, the Q of the section is very high. Consequently it is possible to obtain a very narrow passband for the arrangement shown in Fig. 1. The degree of coupling may be varied in accordance with well-known filter theory to meet various requirements of bandwidth and attenuation.

Many modifications in the arrangement of Figs. 1 and 2 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 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, as illustrated, the lateral extent of ground planes 15, 15' prevents significant radiation of energy in a lateral direction, thus preventing interference with adjacent lines or vice versa. For ground plane spacings less than a half-wavelength (usually desirable), 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.

Fig. 3 illustrates two resonant filter sections comprising elongated strips 31, 32 coupled in end-to-end relationship between input section 17 and output section 19. The various constructional details illustrated in Figs. 1 and 2 and discussed above are omitted in Fig. 3 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 arrangement shown in Fig. 3 is generally equivalent to two tuned resonant circuits in series between input and output. Either strip 31 or 32 may be considered to couple the other strip to the input or output line as the case may be. The filter functions as a bandpass filter which, with proper design, will have a much sharper skirt selectivity than that of the filter illustrated in Fig. 1. In a conventional double-tuned filter two resonant circuits are tuned to the same frequency and the coupling therebetween selected so that the overall attenuation characteristic has a double hump. A similar result can be obtained with the arrangement of Fig. 3 by making filter sections 31 and 32 resonant at the same frequency in the middle of the desired passband and adjusting the coupling between filter sections and between respective sections and the adjacent input and output lines.

As will be understood by those skilled in the art, the physical length of a resonant section such as 31 will not be exactly a half-wavelength or multiple thereof at the resonant frequency due to fringe effects and coupling to adjacent elements. In the arrangement shown in Fig. 3 the approximate physical length can be predetermined in the following manner. Assume that the coupling capacitance between input strip 17 and resonant strip 31 is C_c and that the same capacitance exists between resonant strip 32 and output strip 19. Also assume that the coupling capacitance between resonant strips 31 and 32 is C_c . It will be understood that each coupling capacitance is composed not only of the direct series capacitance between the ends of adjacent strips, but also includes the shunt capacitances from each strip to the ground planes. Then, for an effective length of a half-wavelength, the actual physical length L of the resonant strip can be approximately determined from the following equation:

$$L + \frac{2C_c + C_c}{\bar{C}} = \frac{\lambda}{2} \quad (1)$$

In this equation $\bar{C}$ is the per unit capacitance of the transmission line from which the filter element is cut. In deriving this equation, the coupling capacitance C_c between two filter sections is assumed to be replaced by an equivalent series circuit consisting of two equal capacitors each of capacitance $2C_c$, and each capacitor is assumed to affect only its adjacent resonant section.

Ordinarily, it is the characteristic impedance Z_0 rather than the capacitance per unit length which is known for a given transmission line. In this event, Equation 1 can be stated in terms of characteristic impedance by making use of the following equation:

$$\bar{C} = \frac{1}{vZ_0} \quad (2)$$

In Equation 2, v is the velocity of propagation in the line. Ordinarily it may be taken to be the free space velocity of propagation, but where necessary it may be taken as the velocity of propagation in the medium in which λ is measured.

$$v = f\lambda \quad (3)$$

where f is the frequency corresponding to λ .

$$f = \frac{\omega}{2\pi} \quad (4)$$

where ω is the angular velocity corresponding to f .

By conventional mathematical manipulation, Equations 2, 3, 4 can be inserted in Equation 1 to obtain the following:

$$(2\pi L/\lambda) + \omega Z_0 (2C_c + C_c) = \pi \quad (5)$$

For a single element filter, such as that shown in Figs. 1 and 2, the quantity $2C_c$ in Equation 5 can be replaced

by C_c , assuming that the two end capacitances are the same. This gives:

$$(2\pi L/\lambda) + 2\omega Z_0 C_c = \pi \quad (6)$$

With the coupling capacitances known, L can be determined approximately from the preceding equations. Direct measurement of the coupling capacitances may be difficult. It is possible to determine the coupling capacitance as a function of separation by building a single element filter with identical end coupling spaces and measuring length L and wavelength λ at resonance. With Z_0 known and ω computed for the measured λ , the coupling capacitance C_c can be computed from the above Equation 6. If this is determined for various spacings, a suitable chart can be prepared for use in calculating more complicated filters.

The foregoing equations are limited to cases where coupling and end capacitances are small, which is the most useful situation, particularly for relatively narrow band filters. More elaborate theory can be derived for other cases, particularly broad band filters, or an empirical approach can be employed. As an example of magnitudes involved, in one microwave filter for a line having a 50 ohm characteristic impedance the theoretical length of a half-wave element was 2 inches but, because of coupling and fringing capacitances, the actual length of the resonant element was 1.75 inches. In this case the 50 ohm line employed ground planes spaced one-half inch apart.

The arrangement of Fig. 3 illustrates two filter sections between input and output sections. Three or more resonant sections may be employed in order to provide additional resonant circuits so as to enhance the frequency selective characteristics of the filter.

To avoid spurious responses, it is usually desirable to limit the width of each resonant strip, and also the separation of the group 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 the ground planes is also less than a half-wavelength of the energy to be transmitted. In one specific embodiment which has been successfully operated, both the width of the strip and the spacing between ground planes were made equal to one-quarter wavelength, the characteristic impedance for this embodiment being in the convenient region near 60 ohms.

In practical applications it is often required to make the characteristic impedance of the strip line match other components or lines. This can be accomplished by changing the ratio between the width of the conductive strips and the spacing of the ground planes. As the ratio becomes greater, the impedance decreases. The thickness of the conductive strip (or the separation of the strips by the insulating sheet in the case of paired strips) also has an effect on the impedance, greater ratios between thickness and separation of ground planes yielding lower impedances. In general it is found desirable to form the resonant filter sections with the same configuration as the input and output transmission line sections, but in some cases it may be desirable to employ a transformation ratio and the configurations may be altered accordingly. For example, the wider the resonant strip the higher the Q , so that resonant strips wider than the transmission line strip may sometimes be useful.

With two or more resonant strips employed in a filter, those skilled in the art will 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 application.

When a number of resonant strips are coupled end-to-end as illustrated in Fig. 3, in some cases the length may

become cumbersome. In accordance with the present invention it is also possible to arrange the resonant elements so that they couple transversely or side-to-side. This is illustrated in Fig. 4, wherein resonant strips 33, 34 are laterally spaced to form a broadside arrangement. In this arrangement the coupling between filter elements is controlled by the spacing between the sides of the strips. The resonant strips may be coupled to input and output strips in end-to-end fashion, as shown. If desired, additional resonant strips can be arranged side-by-side between input and output lines. As an aid to design, it may be mentioned that side-to-side coupling is generally less than end-to-end coupling for a given spacing. If desired, conductive coupling may be employed as described hereinafter in connection with Fig. 11.

Referring now to Fig. 5, a filter arrangement is shown which is similar to that of Fig. 3 but incorporates an additional feature of the invention. With a strip of resonant length, the current will be zero at each end of the strip but the voltage will be a maximum. Hence the effect of fringe fields at each end of the resonant strip will be relatively greater and losses in the adjacent portions of the insulating sheet 21 may appreciably reduce the Q of the resonant circuit. To avoid these losses, the portions of the insulating sheet 21 in the immediate vicinities of the ends of the resonant strips are advantageously removed. Thus, insulating sheet 21 is cut out to form apertures 35, 36 and 37. The dimensions of the cut-out portions will depend upon the particular insulating material employed and the amount of loss therein. Generally speaking, it is most important to cut out the material directly between the ends of the adjacent strips, as illustrated in Fig. 5a, but in some cases the removal of additional material further reduces losses. In this manner the portions of the insulating sheet are removed in the regions where electromagnetic fields couple energy from one line section to another, thereby improving the efficiency of energy transfer. When a transverse coupling is used as shown in Fig. 4, the insulating sheet may be removed from between the resonant strips 33, 34 near the ends thereof.

Resonant strips can also be coupled to each other or to input or output transmission lines by a combination of longitudinal and transverse coupling. Such an arrangement is shown in Fig. 6. In this figure a pair of resonant strips 31, 32 are coupled between input and output lines 17, 19 in end-to-end relationship in the manner shown in Fig. 3. In addition, a conductive strip 41 is laterally displaced from the resonant strips 31, 32 and overlaps the ends thereof. Thus, resonant strips 31, 32 are coupled not only by the direct end-to-end coupling, but also by the lateral coupling of the ends of each resonant strip to strip 41. The size and spacing of strip 41 can be changed to alter the coupling. Such coupling provides additional control over the characteristics of the filter. Strip 41 may be non-resonant by making it substantially shorter than a half-wavelength or, if desired, it can be made resonant so as to improve the characteristics of the filter for a desired use. In the latter case it serves as a shunt filter while at the same time affecting the coupling between strips 31 and 32.

If desired, a laterally displaced coupling strip may be disposed to overlap the ends of either of strips 31, 32 and the adjacent input or output line, respectively, to add coupling.

Referring now to Fig. 7, for some applications it may be desirable to incorporate a wave trap in a bandpass filter. Such a trap may be placed near one end of the passband to improve the sharpness of cutoff, or the trap frequency may be substantially removed from the desired passband so as to assure attenuation of other unwanted frequencies. Fig. 7 shows a bandpass filter arrangement similar to that of Fig. 3 but with an additional strip 42 of appropriate resonant frequency arranged perpendicularly to the other elements of the filter near the adjacent ends

of resonant strips 31, 32. Resonant strip 42 is hence electromagnetically coupled to the other strips and functions in a manner analogous to a shunt wave trap. In place of a single strip 42, two or more coupled strips may be employed if required for a given application. Also, while the shunting effect is most pronounced in the position illustrated, strip 42 can be moved along the line to alter its shunting effect.

Before proceeding to a discussion of further embodiments of the invention, a specific example will be given of a filter embodying features already described and designed for a particular application, together with curves applicable thereto.

Fig. 8 shows a plan view of the strip arrangement of a branching filter, each branch having a pair of longitudinally coupled half-wavelength resonant strips. The dimensions are given on the figure.

As actually constructed, a thin sheet 50 of a high grade insulating material composed of fiberglass bonded with Teflon, laminated with sheets of copper of foil thickness on each side thereof, was employed as the central strip section, and the foil was removed on both sides of the insulating sheet except in those areas shown in Fig. 8. Thus the strip arrangement comprised pairs of conductive strips, as shown in Fig. 1. The insulating sheet was supported midway between two extended ground planes spaced one-half inch apart.

The input was supplied to the branching filter by a coaxial line coupling to section 51, the central conductor of the coaxial line being soldered to the apex 52, and the outer conductor joined to the ground planes as in Fig. 1. The tapering of the end of section 51 was found desirable to provide a more perfect match between the strip line and the coaxial line, and is preferred to the square end configuration shown in Fig. 1, although the latter may be employed if desired. From the input section 51 the strip transmission line divided to form two branches 53 and 54. Branch 53 contained two resonant strips 55 and 56 of equal length coupled to an output section 57 which was also provided with a coaxial connection.

Similarly, branch 54 contained two resonant sections 59 and 61 of equal length but slightly longer than those in branch 53, coupled to an output section 62.

The spacings 63 between input and output sections and the adjacent resonant sections were made equal but considerably narrower than the spacing 64 between the resonant strips of each branch. The supporting insulating sheet 50 was cut away, as shown at 65, to reduce losses due to fringe fields at the ends of each resonant strip. The narrower spacings 63 provided relatively tight coupling between each filter element and the adjacent line section, whereas the wider spacings 64 between resonant strips provided looser coupling so as to give a greater band width. Generally speaking, the coupling provided by space 64 largely controls the bandwidth, and that provided by spaces 63 largely controls the amplitudes of the peaks and valleys within the passband.

In order to tune the filter after construction, slight changes in coupling are sometimes required. The coupling can be made looser by trimming the filter strips to reduce their length slightly. It can be made tighter by adding a little solder at the ends of the filter elements. Although these trimming adjustments slightly alter the resonant frequencies of the corresponding resonant strips, it was found that excellent results could readily be obtained.

The performance of the filter of Fig. 8 is shown in Fig. 9, wherein the insertion loss of branch 53 is shown by curve 66, and that of branch 54 by curve 67. The insertion loss within the passband was of the order of 2.5 db. It should be understood that the performance illustrated in Fig. 9 is not necessarily the optimum obtainable with an arrangement such as shown in Fig. 8, since the performance obtained with only a little trimming more than met the specifications for the required appli-

cation and no attempt was made to improve it. The strip elements were of copper without silver plating, so that it is likely that the losses could be further reduced if the added expense of silver-plating were justified.

Referring now to Fig. 10, an arrangement is shown whereby two transmission lines, each having an input and an output, may be coupled together. It will be appreciated that in the preceding figures the filter sections terminate the input line and drive the output line. Therefore the filter sections should be designed so as to match the characteristic impedances of the input and output line sections and ordinarily to transmit energy within the desired passband with maximum efficiency. In some applications it may be desired to couple a small portion of energy from one circuit into another, or to remove energy at a selected wavelength from one line while allowing energy at other wavelengths to be transmitted by that line. In this event one or more resonant filter sections coupled together in any of the manners described hereinbefore may be inserted between the two transmission lines.

Fig. 10 shows a simple example of such a connection. It also illustrates a different manner of supporting the conductive strip elements so as to indicate some of the variations which are possible within the scope of the invention.

In Fig. 10 conductive strip 71 forming a transmission line is supported midway between ground planes 15, 15' by insulating blocks 72 of low loss material. For example, material known as "Polyfoam" has been employed with success. Transmission line 71 has input and output sections which will here be assumed to be sections 73 and 74, respectively. Since the line is essentially non-resonant, supports 72 are advantageously spaced a quarter wavelength apart, although other spacings may be employed, if desired. Similarly, another transmission line comprising conductive strip 75 is supported midway between the ground planes 15, 15' and is here assumed to have input and output sections 76 and 77, respectively. Between strips 74 and 77 are disposed one or more resonant elements to form a filter coupling the two lines.

As specifically shown, a simple one-element filter is employed, consisting of conductive strip 78 coupled between lines 74 and 77 by virtue of the close spacing of its ends with the lines, and supported midway between conductive planes 15, 15' by means of insulating blocks 72. Since strip 78 must be largely self-supporting, it should have sufficient thickness to give adequate rigidity. As specifically shown, the resonant section 78 is one wavelength long and is advantageously supported at voltage nodes by insulating spacers 72. To this end, blocks 72 are positioned approximately a quarter of a wavelength inward from each end of strip 78.

With electromagnetic energy supplied to line 71, frequencies within a relatively narrow band determined by the resonant frequency of strip 78 will be fed to line 75. If it is desired to couple a broader band of frequencies from line 71 to line 75, a multiple resonant filter structure such as described hereinbefore may be inserted between the two lines. It will be understood that strips 71, 75 and 78 may be thin foil-like strips disposed on one or both sides of a sheet of insulating material in the manner described in connection with previous figures, if desired.

As an example of the effectiveness of a circuit arrangement such as that shown in Fig. 10, in one specific embodiment conductive strip 78 was made a half-wavelength long and of sheet copper about $\frac{1}{32}$ inch thick. The width of the conductive strips 71, 75, 78 and the separation of ground planes 15, 15' was half an inch. This gave a characteristic impedance of about 50 ohms. Spacers 72 were of quarter-inch thick Polyfoam. Input section 73 of line 71 was excited in the vicinity of 3000 megacycles by a swept signal generator and the output section 74 was terminated in its characteristic impedance.

One end of line 75 was terminated in its characteristic impedance and a matched detector coupled to the other end. The measured Q was about 2000, and compared favorably with the calculated Q of a comparable coaxial line filter. Since the resonant element 78 was a half-wavelength long, only one pair of Polyfoam spacers was employed and these were placed at the center of the strip.

The configuration was then modified to insert two colinear resonant elements, each a half-wavelength long, between lines 71 and 75. The resultant filter passed frequencies within a bandwidth of about four megacycles (measured between 6 db points) and had an insertion loss of 5.5 db. Of this insertion loss 3 db was due to using matched input and output lines, the remaining 2.5 db being due to the transmission loss of the filter. With closer coupling between the filter and the lines 71, 75, obtained by reducing the space at both ends thereof, the filter was more heavily loaded and had a bandwidth of about 26 megacycles.

In the embodiments described thus far, nonconductive coupling between the transmission line strips and the resonant strip sections, and between resonant strip sections, has been employed. Such coupling has been found very satisfactory, particularly for relatively narrow band operation, that is, for filters which are quite selective. It also serves to isolate portions of the microwave circuit for direct current or very low frequencies. However, it is also possible to employ conductive coupling. Generally speaking, such coupling is stronger and is more suitable for broad band operation. Also, it may be employed when it is desired to connect portions of microwave circuits for direct current, for example, in supplying operating potentials to electronic tubes or crystals.

Fig. 11 is an example of the use of conductive coupling with transversely arranged resonant strip sections. As in previous arrangements, input and output transmission line sections 17, 19 are supported by insulating sheet 21 midway between extended conductive plates 15, 15'. The paired conductive strip arrangement is employed, having matching strips disposed on opposite sides of sheet 21 as indicated at 19'. Resonant strip sections 81 and 82, having a length approximately equal to a multiple of half-wavelengths, are disposed transversely between the input and output lines. As specifically illustrated, they are intended to be approximately a half-wavelength long. Short conductive strips 83 are employed to couple to input and output strips, and strip 88 is used to couple the resonant strips together.

Since the center of a half-wave resonant strip is a voltage node and a current antinode, and the ends are voltage antinodes and current nodes, the impedance at the center is substantially zero and becomes very high at the ends. It is desirable to couple input and output lines to the resonant strips offcenter at a point where the impedance transformation represented by the coupling provides the desired loading on the filter, and to locate strip 88 so that the coupling provides the desired bandwidth. Also, for most efficient transfer of energy, it is desirable to restrict the length of the contact with the resonant strip so that the variation in impedance presented to different points of the connecting strips 83 and 88 will not cause too great a mismatch. Theoretically, point contact would appear to be best, but in practice is not found essential so long as the length of contact along the resonant strip is fairly small. Also, it is desirable to make the connecting strips 83 and 88 relatively short compared to a resonant strip so that they will be non-resonant at the operating frequencies.

As has been pointed out before, since the resonant strips 81, 82 have voltage antinodes at the ends thereof, relatively strong fringe fields exist and may cause losses in the adjacent dielectric. Consequently, in Fig. 11 the portion of the insulating sheet 21 is cut away at the ends of the resonant strips, leaving apertures 85.

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

There are now available foamed polystyrene ("Poly-foam") 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. 10, 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 coaxial line arrangements become very lossy in this range and comparable waveguide units are 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, such as in Figs. 3-8 and 11, 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 requirements of a particular application. Also, it is possible to adapt the configurations to a particular use. For example, a resonant strip can be coupled to an input strip line in end-to-end relationship, but with the resonant strip at an angle to the input line such as the perpendicular arrangement described in connection with Fig. 7. The end of the resonant strip can overlap the end of the input line, or vice versa. The other end of the resonant strip can be coupled to another resonant strip or to an output line either in straight-line end-to-end configuration or, again, at an angle. In this way, if desired, input and output strip sections can be disposed on the same side of a given resonant strip but near opposite ends thereof. Such flexibility in selecting the configuration is advantageous in meeting the requirements of a given application.

We claim:

1. A microwave frequency-selective circuit which com-

prises a pair of conductive surfaces in spaced parallel planes maintained at a common potential to form ground planes, the spacing of said ground planes being less than substantially a half-wavelength at the operating frequency, a thin sheet of insulating material supported midway between said conductive surfaces in parallel relationship therewith, a circuit element resonant within the operating range of said frequency-selective circuit comprising an elongated conductive strip section of length approximately equal to an integral multiple of half-wavelengths at the resonant frequency of said element, said elongated strip section being contiguous with said thin sheet of insulating material and ungrounded with respect to said ground planes, said thin sheet having apertures adjacent the ends of the elongated strip section, said ground planes extending laterally beyond the lateral edges of said elongated strip section a distance at least as great as said spacing of the ground planes, and microwave transmission line means coupled to said elongated section.

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, the spacing of said ground planes being less than substantially a half-wavelength at the operating frequency, a thin sheet of insulating material supported midway between said conductive surfaces in parallel relationship therewith, a pair of conductive strip sections contiguous with said thin sheet of insulating material and disposed with an end of one section adjacent an end of the other section in coupled relationship, at least one of said strip sections forming a circuit element resonant within the operating range of said frequency-selective circuit and having a length approximately equal to an integral multiple of half-wavelengths at the resonant frequency thereof, said one strip section being ungrounded with respect to said ground planes, said thin sheet of insulating material having an aperture extending at least between the adjacent ends of said strip sections, and said ground planes extending laterally beyond the lateral edges of said conductive strip sections a distance at least as great as said spacing of the ground planes.

References Cited in the file of this patent

UNITED STATES PATENTS

2,673,928	Gurewitsch	Mar. 30, 1954
2,751,558	Grieg et al.	June 19, 1956
2,760,169	Englemann	Aug. 21, 1956
2,819,452	Arditi et al.	Jan. 7, 1958
2,820,206	Arditi et al.	Jan. 14, 1958
2,913,686	Fubini et al.	Nov. 17, 1959

FOREIGN PATENTS

601,514	Great Britain	May 7, 1948
513,257	Belgium	Feb. 2, 1953
524,871	Belgium	June 8, 1954
712,306	Great Britain	July 21, 1954

OTHER REFERENCES

Barrett: Electronics, June 1952, pages 114-118.
Arditi: Electrical Communication, December 1953, pages 283-293.
Packard: Electronics, September 1954, pages 148-150.
Fubini et al.: Convention Record of the IRE March 1954, part 8, pages 91-97.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 2,984,802

May 16, 1961

John N. Dyer et al.

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 5, line 63, equation (3), after "f" insert -- λ --;
column 6, line 37, for "group" read -- ground --.

Signed and sealed this 10th day of October 1961.

(SEAL)

Attest:

ERNEST W. SWIDER

Attesting Officer

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Commissioner of Patents

USCOMM-DC