Dec. 31, 1940. W. S. PERCIVAL 2,226,739

ELECTRIC WAVE FILTER FOR THERMIONIC VALVE AMPLIFIERS

Filed Sept. 15, 1938 2 Sheets-Sheet 1

Fig. 1

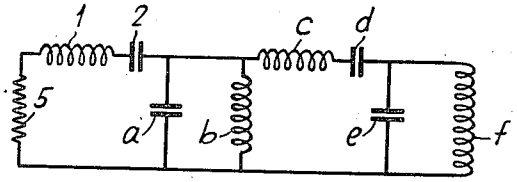


Fig. 1a

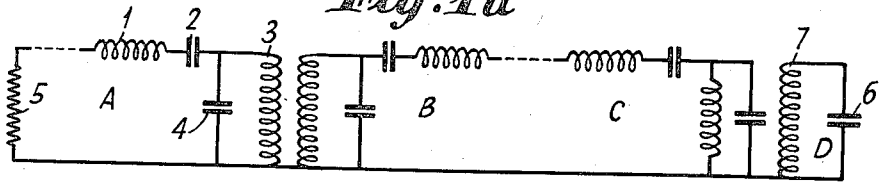


Fig. 2

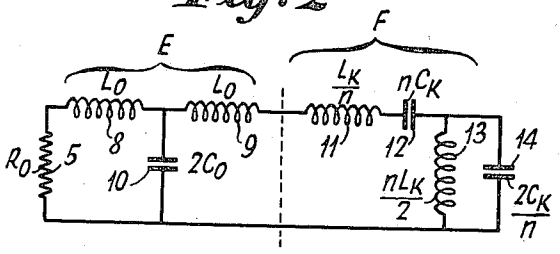


Fig. 4

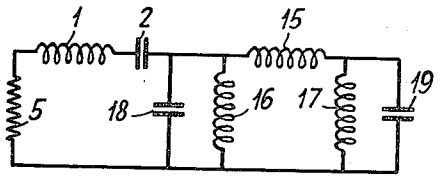


Fig. 3

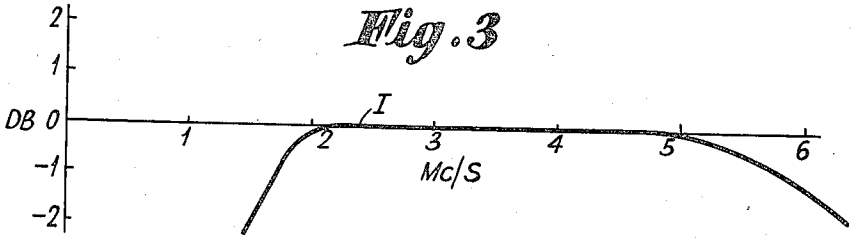


Fig. 5

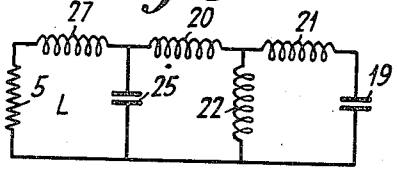
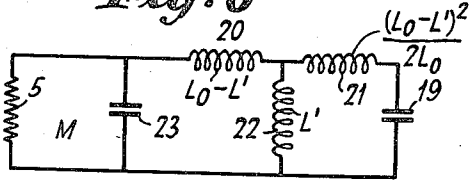


Fig. 6



INVENTOR
W. S. PERCIVAL
BY H. S. Grover
ATTORNEY

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ELECTRIC WAVE FILTER FOR THERMIONIC VALVE AMPLIFIERS

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Fig. 7

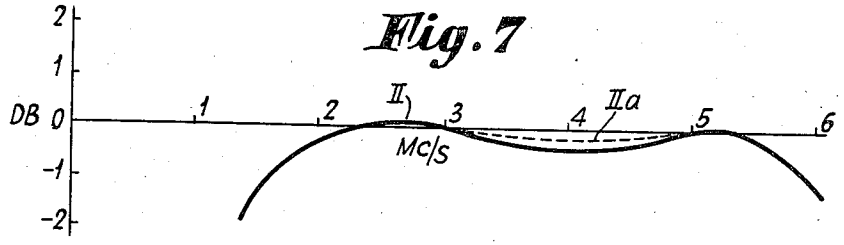


Fig. 8

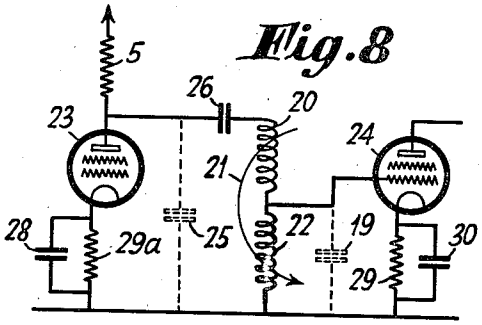


Fig. 9

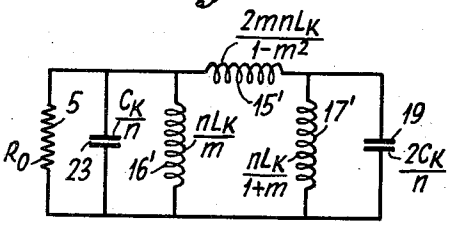


Fig. 10

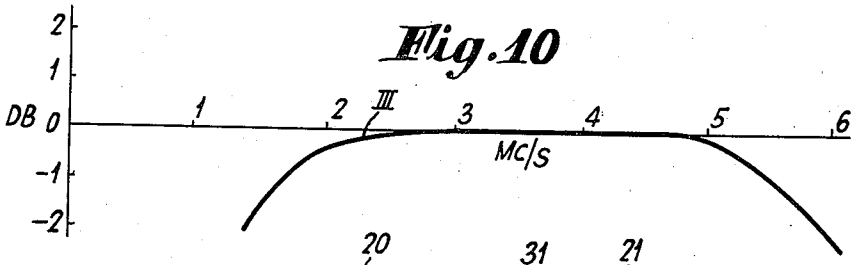


Fig. 11

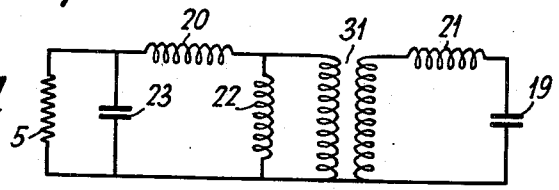
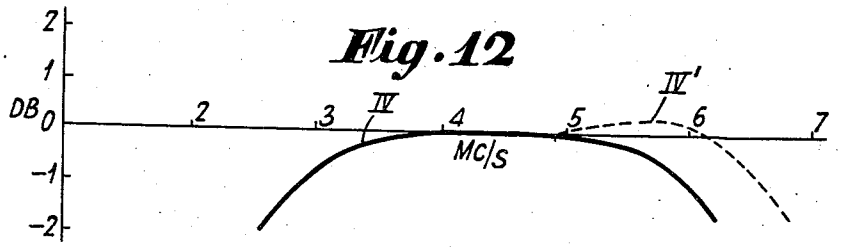


Fig. 12



INVENTOR
W. S. PERCIVAL
BY H. S. Grover
ATTORNEY

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UNITED STATES PATENT OFFICE

2,226,739

ELECTRIC WAVE FILTER FOR THERMIONIC VALVE AMPLIFIERS

William Spencer Percival, Ealing, London, England, assignor to Electric & Musical Industries Limited, Hayes, Middlesex, England, a corporation of Great Britain

Application September 15, 1938, Serial No. 230,016
In Great Britain September 22, 1937

7 Claims. (Cl. 178—44)

The present invention relates to electric wave filters for thermionic valve amplifiers and the like such as are suitable for use in television systems, and is an improvement in the arrangements disclosed and claimed in my copending patent application, Ser. No. 126,317, filed Feb. 18, 1937, and issued as Patent No. 2,156,656 on May 2, 1939.

In the aforesaid application circuit arrangements forming electric wave filters suitable for use in television amplifiers are described in which a high value of the product of pass band and stage gain can be obtained. Circuits of low-pass type and of band-pass type are described, the low-pass type filters being in the form of filters which are matched at one end to prevent reflection and being provided with a mid-shunt termination at the other end with an additional capacity equal to the shunt capacity already existing, while the band-pass type circuits include a shunt inductance in addition to the shunt capacity, the inductance being provided to tune the additional shunt capacity to the mean frequency of the pass-band.

In the case of filters of the band-pass type however, ordinary "constant K" type filters comprise a large number of elements and are somewhat difficult to adjust.

The object of the present invention is to provide band-pass type circuits in accordance with the teaching of the above mentioned application, which may be readily made up and adjusted.

According to the present invention, the filter is of the band-pass type and comprises a plurality of prototype half-sections, the arrangement being such that at least one section of the filter includes no series tuned elements.

In accordance with one feature of the invention a filter may be provided in which part of the filter is low-pass and part band-pass, the two parts being substantially matched over the effective range of the band-pass part.

In accordance with another feature of the invention a band-pass filter may be provided comprising one or more half-sections derived from "constant" K type half-sections in such a way that either series inductance elements or series capacity elements, and preferably the latter, are made to disappear.

In order that the method of carrying the invention into practice may be fully understood, the same will now be described with reference, by way of example, to the accompanying drawings in which:

Figure 1 shows a typical band-pass filter made up of "constant K" sections or half-sections,

Figure 1*a* shows a filter equivalent to that of Figure 1, showing the constituent parts of the filter in expanded form,

Figure 2 shows a filter according to the present invention comprising a combination of low-pass and band-pass sections,

Figure 3 is a graph showing the response of a filter arranged as shown in Figure 2,

Figures 4, 5 and 6 show other forms of filter according to the invention,

Figure 7 is a graph showing the response of a filter arranged as shown in Figure 5,

Figure 8 shows a filter amplifier of which the circuit is effectively that represented in Figure 5,

Figure 9 shows a further form of filter in accordance with the present invention, and equivalent to that shown in Figure 6,

Figure 10 is a graph showing the response of a filter arranged as shown in Figure 6 or 9,

Figure 11 shows a further form of filter provided according to the invention, and

Figure 12 is a graph showing the response of a further form of filter in accordance with the invention.

The arrangement shown in Figure 1, is a band-pass type circuit in accordance with the above mentioned application. This comprises a series branch comprising inductance **1** and condenser **2** in series and a shunt branch including condenser *a* and inductance *b* in parallel, and a further series branch including inductance *c* and condenser *d* in series with condenser *e* and inductance *f* in shunt.

The filter is terminated at one end by a resistance **5** having a value substantially equal to the characteristic impedance of the network and the inductance *c* and condenser *d* provide an unmatched termination as indicated in Figure 1*a*. For convenience in explaining the present invention the circuit of Figure 1 has been resolved, in Figure 1*a*, into its three component half-sections A, B and C respectively, each comprising an inductance such as **1** in series with a capacitance such as **2**, and a shunt inductance such as **3**, and a shunt capacitance such as **4**, only the elements of half-section A and the terminating elements being referenced. The filter is matched at one end by terminating resistance **5** and has an unmatched termination D providing the initial shunt reactance at the other end, said termination comprising capacitance **6** and inductance **7** in shunt, the unmatched termination providing in association with the shunt branch of the preceding half-section of the filter an initial shunt reactance equal to the full shunt reactance of a section of the filter.

It will be seen that the above described filter comprises as many series tuned branches as there are sections in the filter, and as in many cases, the tuning adjustments required are critical, serious limitations are placed on the use of the filter and in addition a large number of elements may be required to make up a filter.

Thus according to one feature of the inven-

tion the number of series tuned arms required may be reduced by constructing a filter of low-pass and band-pass sections in combination. A suitable form of filter is shown in Figure 2. In this filter part E is a T type low-pass filter section comprising series inductances **8** and **9** and shunt capacity **10**, and part F provides a band-pass half-section corresponding to C of Figure 1 and an unmatched termination corresponding to D of Figure 1*a*, the part F including series connected inductance **11** and capacity **12** and shunt connected inductance **13** and capacity **14**. If the shunt capacities are not in the correct ratio this can be adjusted by the method of impedance transformation described in the textbook "Transmission Networks and Wave Filters" by T. E. Shea (Chapman & Hall, 1930) at page 326. This method is referred to more fully in the description with reference to Figure 11 of the drawings.

In most cases, for convenience, the inductances **9** and **11** of Figure 2 would be provided by the inductance of a single coil.

The method of designing a filter of the kind shown in Figure 2 will be readily understood from the following explanation:

For a filter made up of "constant K" type band-pass sections, in which the frequency limits of the pass-band are f_1 and f_2 respectively, the mean frequency is f_m, f^1 and f^1_2 respectively are the frequency limits of the working range of the filter and at which the characteristic impedance of the filter is R, R_0 is the nominal impedance of the filter, the following basic relationships apply:

$$f_1 f_2 = f^1_1 f^1_2 = f_m{}^2 \quad \text{----------} \quad (1)$$

and

$$\frac{f^1_2 - f^1_1}{f_2 - f_1} = \sqrt{1-\left(\frac{R}{R_0}\right)^2} \text{ or } \sqrt{1-\left(\frac{R_0}{R}\right)^2} \quad \text{----} \quad (2)$$

according as to whether R is the mid-series or mid-shunt characteristic impedance.

A low-pass filter may be regarded as a special case of a band-pass filter where $f_1 = f^1_1 = 0$, f_2 having a value f_0, the cut-off point for the filter. Thus for a low-pass filter

$$\frac{f}{f_0} = \sqrt{1-\left(\frac{R}{R_0}\right)^2} \text{ or } \sqrt{1-\left(\frac{R_0}{R}\right)^2} \quad \text{-----} \quad (3)$$

where f is any frequency below the cut-off frequency and R is the corresponding characteristic impedance.

The component values of the elements of the filter have been indicated in Figure 2 of the drawings where R_0 is as above, the nominal impedance of the filter, L_0 and C_0 are the inductance and capacity elements in a half-section of a low-pass filter with cut-off frequency f_0,

$$L_k = \frac{R_0}{2\pi f_m}$$

where f_m is the mean frequency of the band-pass half-section of the filter and

$$C_k = \frac{1}{2\pi f_m R_0}$$

and

$$n = \frac{f_2 - f_1}{f_m}$$

where f_1 and f_2 are the frequency limits of the pass band in the band-pass section, and f_m is the mean frequency thereof.

A very satisfactory arrangement is provided by the case in which the filter of Figure 2 is designed in such a manner that the working range of the band-pass portion coincides with the upper two thirds of the working range of the low-pass portion of the filter.

Assuming that the upper limit of the working range of a "constant K" low-pass section is given by

$$\frac{f_0}{2}$$

the working range of the band-pass part will be from

$$f^1_1 = \frac{f_0}{6} \text{ to } f^1_2 = \frac{f_0}{2}$$

and the mean frequency f_m thereof will be 0.288 f_0.

Now from Equations 2 and 3 above

$$\frac{f_2{}^1 - f_1{}^1}{f_2 - f_1} = \frac{f}{f_0}$$

But

$$\frac{f}{f_0} = \frac{1}{2}$$

thus

$$f_2 - f_1 = 2(f_2{}^1 - f^1_1)$$

thus

$$f_2 - f_1 = \frac{2}{3} f_0$$

thus

$$n = \frac{2}{3} f_0 + 0.288 f_0 = 2.32$$

It is thus possible to calculate the values of the elements in the band-pass part of the filter from the cut-off frequency of the low-pass section having the desired working range.

A characteristic response curve for a filter of the semi-band-pass type as shown in Figure 2 is shown by the curve I in Figure 3, wherein response in decibels is plotted vertically and frequency horizontally.

In this case the value of the various elements of the filter was as follows:

Resistance 5	2,300 ohms.
Inductance 8	36.6 micro-henries.
Capacity 10	13.8 micro-micro-farads.
Inductances 9 and 11 (together)	91.6 micro-henries.
Capacity 12	55.5 micro-micro-farads.
Inductance 13	147 micro-henries.
Capacity 14	20.75 micro-micro-farads.

The frequencies and frequency parameter n for the filter are

$f_0 = 10$ mc./s.
$f_1 = 1.06$ mc./s.
$f_2 = 7.72$ mc./s.
$f^1_1 = 1.67$ mc./s.
$f^1_2 = 5$ mc./s.
$f_m = 2.88$ mc./s.
$n = 2.31$

It is of interest to notice the error in matching between the low-pass and the band-pass parts of the filter shown in Figure 2. For this purpose, the table below indicates the ratio R/R_0 for each section:

Frequency	R/R_0 for low-pass section	R/R_0 for band-pass part
$\frac{1}{6}f_0$	.98	.87
f_m	.96	1.0
$\frac{1}{2}f_0$	.87	.87

It will thus been seen that the mis-match is only

serious in the working range at low frequencies.

The average mis-match may be reduced by raising the impedance of the low-pass portion of the filter, say by 5%. Alternatively, the additional mid-shunt impedance at the open end may be varied to counteract the effect of the mismatch on the amplitude response curve, for example, in the particular case given above it has been found advantageous to change the values of the elements 13 and 14 to 170 micro-henries and 19.6 micro-micro-farads respectively.

In the arrangement according to the invention shown in Figure 4, the two half-sections B and C of the filter shown in Figure 1*a* have been replaced by two *m*-derived half-sections arranged as indicated in column III of the table on page 316 of the aforesaid text book "Transmission Networks and Wave Filters." In the two said *m*-derived half-sections the series capacity elements have been eliminated, giving an arrangement of π-connected inductances 15, 16 and 17 with shunt condensers 18 and 19, the number of components being reduced by using one inductance or condenser to provide the elements of two sections or half-sections of the filter in well-known manner. In this arrangement it will be seen that a series tuned circuit comprising elements 1 and 2 is still necessary for the "constant K" half-section and the arrangement is not very economical as far as the number of elements is concerned.

It is preferred to eliminate series condensers as described rather than series inductances as the latter arrangement gives an improved product of stage gain and band width.

The filter arrangement of Figure 4 may be improved in two ways. Either the "constant K" section may be replaced by a low-pass section L of the same nominal impedance as in Figure 5, or some of the shunt capacity may be sacrificed with a consequent lowering of the product of band width and stage gain and a mid-shunt termination to the filter used including a resistance 5 and condenser 23 in parallel as shown at M in Figure 6. In both cases it can be shown that for a low mean frequency in many cases the values of the π-connected inductances 15, 16 and 17 of Figure 4 are excessive. Thus it is usually preferable to provide equivalent T-connected inductances 20, 21 and 22 as shown in Figures 5 and 6.

The arrangement of Figure 5 is similar to an ordinary inductance coupled band-pass circuit except that the whole of the resistance 5 is at one end. This renders it superior to the ordinary coupled band-pass circuit since the equivalent shunt resistance is higher for a given total capacity. In the same way a low-pass filter amplifier with a shunt capacity termination 19 at an "open" end as shown enables the same pass band to be obtained for a greater total shunt capacity than if both ends are terminated with a resistance. Moreover, the characteristic is flatter over the working range.

In a typical case, a filter in accordance with Figure 5 was made up of elements having the following values:

Resistance 5	2300 ohms.
Inductance 27	36.6 micro henries.
Capacity 25	17.3 micro-micro-farads.
Inductance 20	71.2 micro-henries.
Inductance 22	223 micro-henries.
Inductance 21	8.6 micro-henries.
Capacity 19	20.75 micro-micro-farads.

The amplitude-frequency characteristic in this case is given by curve II in Figure 7.

The frequencies and frequency parameter n for this filter are the same as in the case for which the characteristic is given in Figure 3.

In the case where π-connected inductances such as 15, 16 and 17 of Figure 4 are used instead of the T-connected inductances 20, 21 and 22, the values of the π-connected inductances to give the same effect as the T-connected inductances of values indicated above would be

Inductance 15	82.2 micro-henries.
Inductance 16	2125 micro-henries.
Inductance 17	258 micro-henries.

Thus it will be readily seen that the T-connection of the inductances is to be preferred.

In the particular case given, it was found that the response curve might be made flatter as indicated at II*a* in Figure 7 by slightly adjusting the values of the T-connected inductances 20, 21 and 22 as follows:

Inductances 20	71.9 micro-henries.
Inductances 22	202 micro-henries.
Inductances 21	7.8 micro-henries.

A typical filter amplifier forming a wave filter in accordance with Figure 5 is shown in Figure 8 of the drawings, corresponding elements in Figures 5 and 8 being indicated by the same reference numerals. The amplifier comprises two valves 23 and 24 shown as of the screen grid type. The terminating resistance 5 of the filter is constituted by the anode load resistance of the valve 23, the shunt capacity 25 of the low pass section L of the filter is represented in dotted lines in Figure 8 and is actually the anode to cathode capacity of the valve 23. The condenser 26 is a coupling condenser and is so large that the filter constants are not affected by it. The inductances 20, 21 and 22 are included in the input of valve 24 as shown, the inductance 21 being constituted by coupling between inductances 20 and 22 indicated by the line linking the two coils. The capacity 19 is shown dotted and is constituted by the grid-cathode or input capacity of the valve 24. The cathode-earth lead of each valve includes a biasing resistance 29*a* and 29 and associated by-pass condensers 28 and 30.

The filter arrangement of Figure 6 is a preferred alternative to the arrangement of Figure 5. The form of the half-sections used in deriving the filter is that of the shunt derived half-section shown in the bottom horizontal row of Figure 9 in the paper presented before the Institution of Post Office Electrical Engineers on "The Design and Construction of Electric Wave Filters," by R. J. Halsey, the notation used in describing the arrangement of Figure 2 in the present case being due to Halsey and followed in the aforesaid Figure 9 of the paper. Using the form of half-section referred to, an arrangement similar to that of Figure 6 of the present drawings is obtained but having π-connected inductances 15^1, 18^1, and 17^1 as shown in Figure 9 of the present drawings instead of the T-connected inductances 20, 21 and 22 as shown in Figure 6.

The method of arriving at the form of filter shown in Figure 6 will be described in the first place with reference to Figure 9, which shows a filter similar to that shown in Figure 6 except for the different arrangement of inductances mentioned, parts in Figure 9 corresponding to those shown in Figure 6 being similarly numbered. Thus, referring to Figure 9, assuming that the working pass-band or working range of

the filter is to be half the theoretical pass band, then again adopting Halsey's notation, we have

$$f_2^1-f_1^1=\frac{f_2-f_1}{2} \quad \text{----------(4)}$$

also

$$f_2^1 f_1^1=f^2m=f_2f_1$$

Thus eliminating f_1 from Equation 4 and transposing we have

$$f_2-\frac{f_1^1f_2^1}{f_2}=2(f_2^1-f^1_1)$$

Thus $f_2^2-2(f_2^1-f_1^1)f_2-f_1^1f_2^1=0$

$$f_2=f_2^1-f^1_1\pm\sqrt{(f_2^1-f_1^1)^2+f_2^1f_1^1}$$

Thus writing

$$A=\frac{f_2^1f_1^1}{(f_2^1-f_1^1)^2}$$

We see that

$$f_2=(f_2^1-f_1^1)(1+\sqrt{1+A})$$

Likewise it can be shown that

$$f_1=(f_2^1-f_1^1)(-1+\sqrt{1+A})$$

Thus, for a given working range, f_1 and f_2 can both be calculated. For convenience, as in the case of Figure 2, the theoretical values of the elements of Figure 9 have been inserted in the figure, the Halsey notation being followed except that the symbol m has been used instead of

$$m2 \text{ for } \frac{f_1}{f_2}$$

As already mentioned the values for the π-connected inductances thus obtained are excessive and it is preferred to transform to a T-connected arrangement as shown in Figure 6, using the method described in the aforesaid text book by Shea at page 93. The values of the T-connected inductances thus obtained are indicated in Figure 6, where

$$L_0=\frac{4R_0^2C_0}{A} \text{ and } L_1=\frac{L_0}{\sqrt{1+A}}$$

and

$$C_0=\frac{C_K}{\eta}$$

In a typical case in a filter of the form shown in Figure 6, the values of the elements were as follows:

Resistance 5	2300 ohms.
Capacity 23	10.4 micro-microfarads.
Inductance 20	71.2 micro-henries.
Inductance 22	223 micro-henries.
Inductance 21	8.6 micro-henries.
Capacity 19	20.75 micro-microfarads.

The characteristic in this case is shown by curve III in Figure 10, the frequencies and frequency parameter n for the filter again being substantially in accordance with that given for the filter of which the characteristic is given in Figure 3.

The characteristic of the filter may be rendered somewhat flatter by slightly adjusting the values of certain of the elements as follows:—

Inductance 20	69 micro-henries.
Inductance 22	277 micro henries.
Inductance 21	10.7 micro-henries.
Capacity 19	18.2 micro-micro-farads.

In a case where π-connected inductances are used as shown in Figure 9, the values of these inductances would be

Inductance 16^1	2125 micro-henries.
Inductance 15^1	82.5 micro-henries.
Inductance 17^1	258 micro-henries.

It will readily be understood that, as in the case of the arrangement of Figure 5, inductance 21 of Figure 6 may be produced by coupling between inductances 20 and 22.

The circuits of Figures 5, 6 and 9 are limited to a particular ratio between the shunt capacities, the ratio in the case of Figures 6 and 9 being 2:1, and it may be awkward, in practice, to provide a filter with the requisite capacity ratio due to the fact that these capacities in question are usually the inter-electrode capacities of valves used in the circuit. While one of the valve capacities might be suitably built out to the required value with additional capacity it is more frequently preferred to insert a transformer having a suitable ratio of transformation between the two capacities to enhance the effect of one of the capacities relatively to that of the other. In this way the product of pass band and stage gain is maintained at the maximum.

For example a transformer may be arranged between the inductances 22 and 21 of Figure 6 as shown at 31 in Figure 11.

In this case if the transformer 31 is ideal and has a voltage transformation ratio ϕ, it may be shown following the reasoning in the aforesaid text-book by Shea at page 326, that the effective value of inductance 21 is given by

$$(L_0-L^1)\frac{2\phi^2}{2L_0}$$

and of capacity 19 by

$$\frac{2C_0}{\phi^2}$$

where

$$C_0=\frac{Ck}{\eta}$$

However, as a transformer may be replaced by a system of π- or T-connected inductances, instead of providing a transformer to vary the effect of the capacity 19, the values of inductances 20, 21 and 22 may be selected so as to give this result.

In this case the values of the inductances become

$$\text{Inductance } 20=L_0-\phi L^1$$

$$\text{Inductance } 21=\frac{\phi}{2}(\phi L_0-2L^1)\frac{\phi L^{12}}{L_0}$$

$$\text{Inductance } 22=\phi L^1$$

It may be shown that with the inductances arranged to produce the effect of a transformer as above described, under certain conditions, the inductance in either the right-hand limb or the left-hand limb of the T-section of the filter shown in Figure 6 may be made zero.

Thus it may be shown that if inductance 21 is to be eliminated.

$$\frac{L_0}{L_1}=\frac{1}{\phi}\pm\sqrt{\frac{1}{\phi^2}-1}$$

In this case $\phi<1$ for

$$\frac{L_0}{L_1}$$

to be real, so that the ratio of capacity 19 to capacity 23 must be greater than 2:1.

Similarly if coil **20** is to be eliminated, since L^0 must equal ϕL^1 it may be shown that

$$\frac{f_m}{f_2^1 - f_1^1} = \phi^2 - 1$$

and for a real solution of this equation, ϕ must be greater than 1 so that the aforesaid capacity ratio must be less 2:1.

Figure 12 shows, by way of example, the characteristic curve IV of a filter in which coil **20** was eliminated, the remaining elements having the following values:

Resistance 5	1500 ohms.
Capacity 23	18.3 micro-micro-farads.
Inductance 22	82.5 micro-henries.
Inductance 21	82.5 micro-henries.
Capacity 19	12.2 micro-micro-farads.

The frequeniies and frequency parameters n and A for the filter having the characteristic IV of Figure 12 is as follows: f_m=4.1 mc./s., f_1=2.1 mc./s., f_2=7.9 mc./s., f_1^1=2.9 mc./s., f_2^1=5.8 mc./s., η=1.41, A=2.

By reducing the inductance **22** by 12% it was found that the response curve of the filter was modified substantially as indicated by the dotted line IV^1 at the right-hand end of the curve IV.

However, for some capacity ratios, the required mean frequency to permit such elimination may be unsuitable, though it so happens that when, as in the case of the illustrative example given above, the capacity ratio is 1.5:1, the left hand inductance can be caused to disappear if the larger shunt capacity is placed in parallel with the terminating resistance and a mean frequency of about 1.5 times the pass-band is selected.

It will be understood that while only an arrangement of T-connected inductances has been shown for producing the desired transformer effect, an equivalent arrangement of π-connected inductances could be used.

What I claim is:

1. An electric wave filter of the band-pass type comprising a plurality of prototype half-sections, each half-section comprising a series and a shunt reactance, one end of the filter being terminated by an impedance substantially equal to the characteristic impedance of the network, in which for the purpose of maintaining the impedance at the unterminated end of the filter substantially constant over the pass band, the value of the initial shunt reactance is made of the order of that of a full shunt reactance, the arrangement being such that the series portion of at least one section is composed solely of reactance of a single sign.

2. An electric wave filter according to claim 1 in which part of the filter is low-pass and part band-pass, the two sections of the filter being substantially matched with respect to their impedance characteristics over the effective range of the band-pass part.

3. An electric wave filter in accordance with claim 1 comprising a low-pass section to one end of which the terminating impedance for the filter is connected and to the other end of which a band-pass half-section is connected, said band-pass half-section having a shunt reactance which forms the initial shunt reactance of the filter and is made equal to the shunt reactance of a full band-pass section.

4. An electric wave filter according to claim 1 comprising a low-pass section to one end of which the terminating impedance for the filter is connected and to the other end of which a band-pass half-section is connected, said band-pass half-section having a shunt reactance which forms the initial shunt reactance of the filter and is made equal to the shunt reactance of a full band-pass section the arrangement being such that the working range of the band pass portion of the filter corresponds with the upper two-thirds of the working range of the low-pass section thereof.

5. An electric wave filter in accordance with claim 1 including a band-pass section the series portion of which is composed solely of reactance of a single sign, the shunt reactance at one end of the band-pass section constituting the shunt reactance of the filter and being equal to the shunt reactance of a full section.

6. An electric wave filter in accordance with claim 1 including a band-pass section the series portion of which is composed solely of reactance of a single sign, and wherein the filter includes in association with said band-pass section a low-pass half-section to one end of which the terminating impedance for the filter is connected.

7. An electric wave filter according to claim 1 in which part of the filter is low-pass and part band-pass, the two sections of the filter being substantially matched with respect to their impedance characteristics over the effective range of the band-pass part, said band-pass section of the filter comprising an arrangement of 3 T-connected inductances.

WILLIAM SPENCER PERCIVAL.