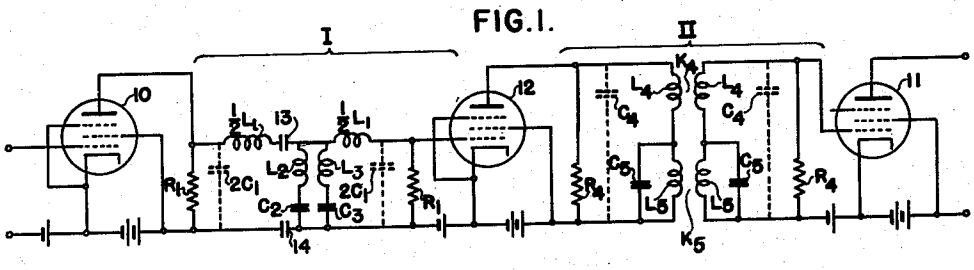
Nov. 28, 1939. H. A. WHEELER 2,181,499

BAND-PASS FILTER

Filed Nov. 10, 1937

FIG.1.



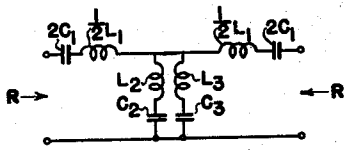




FIG.2.

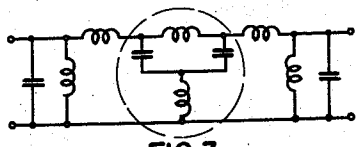
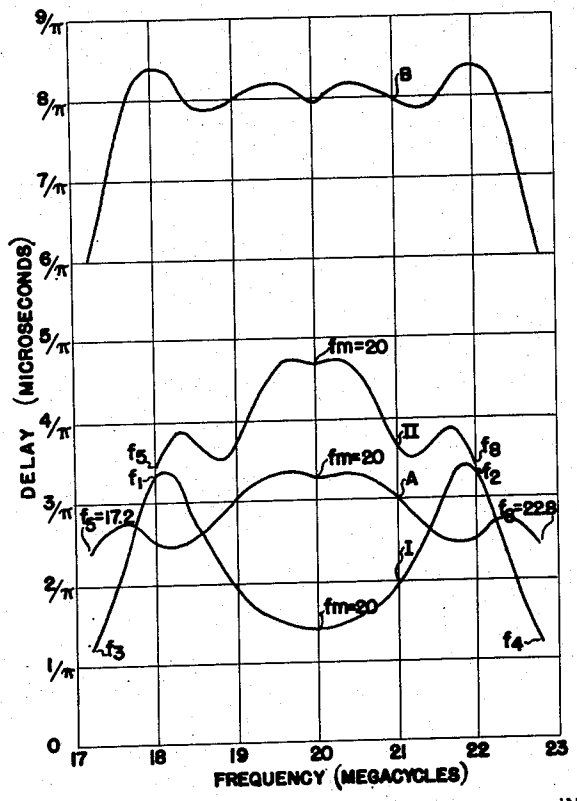


FIG.3.

FIG.4.




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Patented Nov. 28, 1939 2,181,499

# UNITED STATES PATENT OFFICE

2,181,499

## BAND-PASS FILTER

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Application November 10, 1937, Serial No. 173,823

9 Claims. (Cl. 178—44)

This invention relates to band-pass filters and, more particularly, to composite band-pass filters for passing the sideband frequencies of a modulated-carrier wave with a minimum distortion of the modulation-frequency envelope. While the invention is of general application, it is especially suitable for coupling vacuum-tube repeaters of a television signal-translating apparatus.

In many installations, particularly in television signal-translating circuits, it is desirable to pass a wide band of frequencies, which band is, however, relatively narrow as compared with the mean frequency of the band, and it is desirable to provide a high attenuation of frequencies just outside the band. In filters of the prior art having such attenuation characteristics, there is an objectionable distortion of the modulation envelope of the band of frequencies passed, while prior art filters which do not have objectionable distortion characteristics also do not have a high attenuation for frequencies just outside of the pass band.

Furthermore, in filters of the prior art which do have a very high attenuation for frequencies just outside of the pass band, the filter circuit is such that an appreciable capacitance across the terminal circuits of the filter is not tolerable. As most electron discharge devices have substantial capacitance between their electrodes, a severe limitation is thus placed upon the use of such filters in high-frequency signal-translating networks.

It is an object of the invention, therefore, to provide a composite band-pass filter for passing a wide band of frequencies which is relatively narrow with respect to the mean frequency of the band, the composite filter haivng high attenuation for frequencies just outside of the pass band and having minimum distortion of the modulation envelope of the band of frequencies passed.

It is another object of the invention to provide a band-pass selector circuit for passing a wide band of frequencies, the circuit having high attenuation just outside the band of frequencies passed, which will tolerate substantial capacitance across the terminal circuits thereof.

It is a further object of the invention to provide a composite band-pass filter comprising component filters coupled in cascade and having time-delay frequency characteristics which are complementary over the band of frequencies passed by the composite filter.

In accordance with the invention, there are provided two or more band-pass filters coupled in cascade. One of the filters is highly selective as against frequencies just outside of the pass band and has a time-delay frequency characteristic in the band which is not constant, but which is symmetrical about the mean frequency of the band and which has maxima and minima at predetermined frequencies within the pass band. A second of the filters also has a time-delay frequency characteristic in the band which is symmetrical about the mean frequency, but which varies in a different manner than, and preferably complementarily to, that of the first filter thus having maxima and minima at predetermined frequencies within the pass band such that points of maxima in the characteristic of said first filter correspond approximately to points of minima in the characteristic of said second filter and vice versa. If such a relationship obtains, the resultant time-delay frequency characteristic is substantially constant with frequency so that the phase-frequency characteristic of the network is approximately linear (uniform time delay) which is a requisite for distortionless transmission of the modulation-frequency envelope. Further, in accordance with the invention, there is provided a band-pass filter which is highly selective against frequencies just outside the band and which can tolerate appreciable capacitance across its terminal circuits. This characteristic is obtained by substituting approximately equivalent circuits for portions of a known filter, said equivalent comprising capacitance across the filter terminals.

For a better understanding of the invention, together with other and further objects thereof, reference is had to the following description taken in connection with the accompanying drawing, and its scope will be pointed out in the appended claims.

Fig. 1 of the drawing is a schematic diagram of a circuit including a composite band-pass filter according to the invention; Figs. 2 and 3 are approximately equivalent simplified circuit diagrams of the two filters of Fig. 1; while Fig. 4 illustrates the time-delay frequency characteristics of the filters of Fig. 1.

Referring to Fig. 1 of the drawing, there is shown a composite filter comprising, in cascade, a filter designated as type I and a second filter designated as type II coupled between two vacuum tubes 10 and 11. The input circuit of the type II filter is shown coupled to the output circuit of the type I filter through vacuum tube 12, although it will be understood that other forms of coupling can be used between the two filters.

The type I filter is of the ladder type comprising two similar inductive mid-series arms, each comprising an inductance $\frac{1}{2}L_1$, and two series-resonant shunt arms comprising reactive elements $L_2$ $C_2$ and $L_2$, $C_3$. Terminating resistors $R_1$ are provided for the type I filter, each shunted by a condenser $2C_1$. The condensers $2C_1$ are shown in dotted lines for the reason that each may be composed in whole, or in part, of the in-

herent interelectrode capacitance of the tube to which the filter is coupled. Condensers 13 and 14 are direct current blocking condensers of negligible reactance at high frequencies so that they do not otherwise affect the operation of the filter.

The type II filter comprises two transformers comprising inductive windings $L_4$, $L_4$ and $L_5$, $L_5$, respectively, having coefficients of coupling $K_4$ and $K_5$, respectively. The primary and secondary windings of each of the transformers have been given a similar designation to indicate that the value of the inductances of the primary and secondary windings are equal in each case. If unequal primary and secondary impedance is desired, the well-known transformer rules may be applied. The primary circuits of the two transformers are connected in series across the output electrodes of vacuum tube 12, while the secondary circuits of the two transformers are connected in series across the input electrodes of vacuum tube 11. Each of the windings $L_5$ is shunted by a condenser $C_5$, while condensers $C_4$ are connected across the input and output terminals of the filter. The condensers $C_4$ are shown in dotted lines to indicate that they may be comprised in whole, or in part, of the interelectrode capacitances of the tubes to which they are coupled. Terminating resistors $R_4$ are provided across the terminals of the type II filter.

The type I filter of the drawing is similar in many respects to the type $VI_1$ filter shown on page 315 of "Transmission Networks and Wave Filters" by T. E. Shea, published by D. Van Nostrand Company, Inc., in 1930. For the purpose of describing the design of the type I filter, reference is made to Fig. 2, which is a filter of the above-mentioned $VI_1$ type. In deriving the type I filter shown in Fig. 1 of the drawing, the resistor R, representing the nominal image impedance of the circuit of Fig. 2, and the series-connected condenser $2C_1$ have been conceived as replaced by an equivalent resistance R' and capacitance $2C_1$ connected in parallel across the filter terminals. R' is then the nominal image impedance of the type I of Fig. 1, and is matched approximately at the terminals by the actual resistors $R_1$, $R_1$. This substitution is desirable for the reason that a filter of the type shown in Fig. 2 will not tolerate appreciable capacitance across its terminals, while the derived filter, that is, the type I, will tolerate substantial capacitance $2C_1$ across its terminals. In the embodiment shown in Fig. 1, this terminal capacitance may be partly composed of the interelectrode capacitance of the tube to which the terminals are coupled. Assuming the band width to be much less than the mean frequency of the band, the value of R is very much less than the reactance of $2C_1$ at frequencies within said band. This is the basis for deriving from the series resistance R and the capacitance $2C_1$ of Fig. 2, the parallel resistance R' and the equal capacitance $2C_1$ of the type I filter, the two circuits being approximately equivalent under these conditions. The equivalent parallel combination, therefore, includes parallel capacitance substantially equal to that of the series condenser and parallel resistance much greater than the reactance of this condenser at the frequencies of the band. In the formulae which are given hereinafter with respect to the type I filter, R' is the value of the shunt resistance equivalent to the series resistance R. The terminating resistance $R_1$ of Fig. 1 may or may not be equal to R', but has a value of the same order of magnitude. Making $R_1$ slightly greater has the advantage of securing slightly more uniform gain and slightly greater attenuation outside of the band, but has the disadvantage of increasing the variation of time delay with respect to frequency within the band. While the filter of type I is theoretically not an ideal band-pass filter, its derivation being based on an approximation, its characteristics are substantially those which would be obtained by the above-mentioned type $VI_1$ filter.

The type II filter shown in Fig. 1 is identical to the filter described in United States Letters Patent No. 2,081,861, granted May 25, 1937, on the application of Harold A. Wheeler. However, a restriction is here placed upon the design of the type II filter in that it must be designed for a band width which is considerably less than the mean frequency of the band in order to ensure a time-delay frequency characteristic which is symmetrical about the mean frequency of the band. The type II filter involves two tuned transformers, one of which is more effective in passing the upper part of the band and the other of which is more effective in passing the lower part of the band. The limiting frequencies of the individual pass bands are related in a geometric progression. For the best performance (maximum gain) the capacitance across the terminals is minimized and includes only the inherent capacitance of the circuit elements connected thereto (vacuum tubes, leads, windings, etc.).

The time-delay frequency characteristics for the type I and the type II filters are shown in Fig. 4 by the curves designated as I and II, respectively. The time delay of a filter, at any particular frequency, as used herein, is defined as usual as the slope of the phase-frequency characteristic at that frequency. It, therefore, has the dimension of time and may be conveniently expressed in microseconds as in Fig. 4. It is well known that a linear phase-frequency characteristic, that is, one of uniform slope and, therefore, of uniform delay, is one requirement for distortionless transmission of a modulated-carrier wave. The time-delay frequency characteristics show up much more critically any irregularities of the phase-frequency characteristic and are, therefore, especially useful in analysis.

In order to explain the delay-correcting properties of the type II filter, reference is made to Fig. 3. This figure shows a circuit which is electrically the equivalent of the double-transformer type II filter in so far as its transmission characteristics are concerned. This equivalent network has, in the dotted circle, four elements in a form which is commonly known as a bridge T type of phase-correcting network. These elements in themselves have negligible effect on the attenuation characteristics, which are determined mainly by the elements outside the circle. The elements outside the circle are the equivalent of a single transformer filter. The network of Fig. 3 could be employed as an alternative form of the type II filter, but would have the disadvantage of requiring additional circuit elements in place of the mutual inductance of the transformers and of requiring insulating condensers, such as are shown in the type I filter. Furthermore, the circuit of Fig. 3 has another disadvantage in not tolerating capacitance to ground from the elements in the circle. Such capacitance to ground is unavoidable and is tol-

erated at all junctions in the arrangement of the type II filter.

Inspection of the curve I indicates that the time delay in type I is minimum at the center frequency of the band and a maximum near the limiting frequencies of the band, while in the type II filter the reverse is true. Therefore, if two of these filters are used in series or cascade, the time-delay characteristics of one are corrected to a large extent by the time-delay characteristics of the other, that is, the composite time-delay frequency characteristic of the two filters is more nearly level than that of type I alone. Such a characteristic corresponds to a more nearly linear phase-frequency characteristic and, therefore, less distortion. Curves I and II of Fig. 4 are for filters having the same cutoff frequencies, arbitrarily chosen as 18 and 22 megacycles. It will be seen that the frequencies at which the time-delay characteristic of the type II filter is a minimum can be made to coincide with those at which the time-delay characteristic of the type I filter is a maximum if the type II filter is designed to pass a wider band of frequencies. Curve A of Fig. 2 shows the time-delay characteristic for a type II filter having cutoff frequencies of 17.2 and 22.8 megacycles, respectively. Widening the band of the type II filter inherently decreases the delay and the amount of delay correction obtainable in one section. However, two or three sections of the type II filter may be employed to secure almost exact correction for one section of the type I filter. Curve B of Fig. 4 shows the resultant time delay which is obtained by combining two of the type II filters having characteristic curves as represented by curve A with a type I filter having a charatceristic curve as represented by curve I of Fig. 4. The extension of the band width of the type II filter as shown by curve A of Fig. 4 only slightly decreases the amount of attenuation secured outside the band, since that is secured mainly in the type I section.

While the composite band filter above-described may be designed for operation over a wide range of conditions, there are given herewith, by way of example, the circuit constants of a particular broad band composite filter for operating over given frequency ranges and embodying the invention in the form described above. The following circuit values have been realized experimentally as closely as possible and include such effects as inherent capacitance or inductance of wiring and of vacuum-tube circuits associated with the filters:

REPRESENTATIVE CIRCUIT VALUES FOR TYPE I FILTER

$f_m$=mean frequency of band=15.7 megacycles
$m$=factor in design formula=0.707
$f_1$=lower cutoff frequency=13.75 megacycles
$f_2$=upper cutoff frequency=18 megacycles
$f_3$=frequency of maximum attenuation below band=13 megacycles
$f_4$=frequency of maximum attenuation above band=19 megacycles
R=735 ohms
R′=5000 ohms
$R_1=R'$=5000 ohms
$2C_1$=5.3 μμf.
$C_2$=4.23 μμf.
$C_3$=6.12 μμf.
$\frac{1}{2}L_1$=19.4 μh.
$L_2$=16.8 μh.
$L_3$=24.2 μh.

REPRESENTATIVE CIRCUIT VALUES FOR TYPE II FILTER

$f_m$=mean frequency of band=15.7 megacycles
H=factor in design formulae=0.88
$f_5$=lower cutoff frequency=13 megacycles
$f_6$=14.76 megacycles
$f_7$=16.74 megacycles
$f_8$=upper cutoff frequency=19 megacycles
($f_6$ and $f_7$ are frequencies in the band chosen so that $f_5$, $f_6$, $f_7$, and $f_8$ are in geometrical progression).
$C_4$=5.3 μμf.
$C_5$=94 μμf.
$L_4$=18.4 μh.
$L_5$=1.17 μh.
$K_4=K_5$=0.126
R″=5000 ohms
$R_4$=1.4 R″=7000 ohms

TABLE OF DESIGN FORMULAE

*Type I filter*

$$f_m=\sqrt{f_1f_2}=\sqrt{f_3f_4}$$

$$m=\sqrt{1-\frac{(f_2/f_m-f_m/f_2)^2}{(f_4/f_m-f_m/f_4)^2}}$$

$$(f_2-f_1)<(f_4-f_3)<<f_m$$

$$\frac{f_4-f_3}{f_2-f_1}=\frac{1}{\sqrt{1-m^2}}$$

$$R=\frac{f_2-f_1}{4\pi f_m^2mC_1}$$

$$R'=\frac{m}{4\pi(f_2-f_1)C_1}=\left(\frac{mf_m}{f_2-f_1}\right)^2R$$

$$C_1=\frac{f_2-f_1}{4\pi f_m^2mR}=\frac{m}{4\pi(f_2-f_1)R'}$$

$$C_2=\frac{4C_1}{1+(f_4/f_m)^2}\cdot\frac{m^2}{1-m^2}$$

$$C_3=\frac{4C_1}{1+(f_m/f_4)^2}\cdot\frac{m^2}{1-m^2}$$

$$L_1=\frac{1}{4\pi^2f_m^2C_1}$$

$$L_2=\frac{1}{4\pi^2f_4^2C_2}$$

$$L_3=\frac{1}{4\pi^2f_3^2C_3}$$

*Type II filter*

$$f_m=\sqrt{f_5f_8}$$

$$h=\frac{f_5}{f_6}=\frac{f_6}{f_7}=\frac{f_7}{f_8}=\sqrt[3]{\frac{f_5}{f_8}}$$

$$C_4=\frac{1}{2\pi(f_8-f_5)R''}$$

$$C_5=\frac{(1+h^6)^2C_4}{h^2(1-h^4)^2}$$

$$L_4=\frac{(1+h^2)^2}{8\pi^2f_7^2(1+h^6)C_4}$$

$$L_5=\frac{(1+h^6)}{8\pi^2f_5^2C_5}$$

$$k_4=k_5=\frac{1-h^2}{1+h^2}$$

While there has been described what is at present considered to be the preferred embodiment

of the invention, it will be apparent to those skilled in the art that various changes and modifications may be made therein without departing from the invention, and it is, therefore, aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What is claimed is:

1. A composite band-pass filter comprising, a first component filter having predetermined cutoff frequencies and a predetermined time-delay characteristic, said time-delay characteristic having maxima and minima at predetermined frequencies within said band, a second component filter having predetermined cutoff frequencies and a predetermined frequency time-delay characteristic, the frequency time-delay characteristic of said second component filter having maxima and minima at predetermined frequencies within its pass band, said cut-off frequencies and the reactive constants of said second component filter being so proportioned with respect to those of said first component filter that points of maxima in its time-delay characteristic correspond approximately to points of minima in the time-delay characteristic of said first component filter, and points of minima in the characteristic of said second component filter correspond approximately to points of maxima in the characteristic of said first component filter.

2. A composite band-pass filter comprising, a first component filter having input and output pairs of terminals and shunt and series reactive arms, two series-resonant circuits coupled in parallel as a shunt arm of said first filter, two inductors in adjacent series arms, and a resistive-capacitive network including shunt capacitance coupled in parallel across one of said pairs of terminals, said network being the approximate equivalent over said band of the mid-series image impedance and the condenser of the series arm of a filter of the m-type which corresponds to said first filter, said first component filter having predetermined cutoff frequencies and a predetermined frequency time-delay characteristic, a second component filter having predetermined cutoff frequencies and a predetermined frequency time-delay characteristic coupled in cascade with said first filter, the reactive constants and cutoff frequencies of said component filters being so proportioned that said time-delay characteristics are complementary over the band of frequencies passed by said composite filter.

3. A composite band-pass filter for passing frequencies of a given band comprising, a first component filter of a type having a frequency time-delay characteristic with maxima near the limiting frequencies of said band, a second component filter coupled in cascade with said first filter and comprising the combination of a plurality of constant-k type band-pass filters of similar type and termination connected individually between common terminal circuits, the several filters of said plurality of filters being similarly connected to both terminal circuits, being adapted individually to pass frequency bands spaced by intervening bands each having a width equal to the mean value of the width of the adjacent pass bands, and being relatively poled and proportioned to pass a resultant continuous band comprising said pass bands and intervening bands, the band of frequencies passed by said second filter being relatively small with respect to the mean frequency of said band, wherefore the frequency time-delay characteristic of said filter is approximately symmetrical about the mean frequency of said band and a minimum near each of the limiting frequencies of said band.

4. A composite band-pass filter for passing a relatively narrow band of frequencies comprising, a first component filter having input and output pairs of terminals and shunt and series reactive arms, two series-resonant circuits coupled in parallel as a shunt arm of said first filter, two inductances in adjacent series arms, a resistance-capacitance network including shunt capacitance coupled across one of said pairs of said terminals, said network being the approximate equivalent over said band of the mid-series image impedance and condenser of the series arm of the corresponding m-type filter, a second component filter including the combination of a plurality of constant-k band-pass filters of similar type and termination connected individually between common terminal circuits, the several band-pass filters being similarly connected to both terminal circuits, being adapted individually to pass frequency bands spaced by intervening bands each having a width equal to the mean value of the widths of the adjacent pass bands, and being relatively poled and proportioned to pass a resultant continuous band comprising said pass bands and intervening bands, the reactive constants and the cutoff frequencies of said component filters being so proportioned that the frequency time-delay characteristics of said component filters are complementary over the band of frequencies passed by said composite filter.

5. A band-pass filter for passing a relatively narrow band of frequencies comprising, input and output pairs of terminals and shunt and series reactive arms, two series-resonant circuits coupled in parallel to form a shunt arm of said filter, two inductances in adjacent series arms, and a resistance-capacitance network including shunt capacitance coupled across one of said pairs of terminals, said network having an impedance approximately equivalent over said band to the sum of the mid-series image impedance and the impedance of the condenser of the series arm of the corresponding m-type filter.

6. A band-pass filter for passing a relatively narrow band of frequencies comprising, input and output pairs of terminals and shunt and series reactive arms, two series-resonant circuits coupled in parallel to form a shunt arm of said filter, two inductances in adjacent series arms, and a resistor and condenser coupled in parallel across one of said pairs of terminals, said resistor and condenser having an impedance approximately equivalent, over said band, to the sum of the mid-series image impedance and the impedance of the condenser of the series arm of the corresponding m-type filter.

7. A band-pass filter for passing a relatively narrow band of frequencies comprising, input and output pairs of terminals and shunt and series reactive arms, two series-resonant circuits each resonant outside said band and near one of the limiting frequencies of said band and coupled in parallel as a shunt arm of said filter, two inductances in adjacent series arms, and a resistance-capacitance network including shunt capacitance coupled across one of said pairs of said terminals, said network being the approximate equivalent over said band of the mid-series image impedance and condenser of the series arm of the corresponding m-type filter.

8. A composite band-pass filter comprising a first component filter having predetermined cutoff frequencies and a predetermined frequency time-delay characteristic which is maximum just inside the cutoff frequencies in the pass band, a second component filter having a predetermined time-delay characteristic which is minimum just inside the pass band of said first component filter, said second component filter being coupled in cascade with said first component filter, the reactive constants of said component filters being so proportioned that said time-delay characteristics are complementary over the major portion of the pass band and so that appreciable phase correction is obtained in the pass band adjacent said cutoff frequencies.

9. A composite band-pass filter comprising a first component filter having predetermined cutoff frequencies and a predetermined frequency time-delay characteristic which is maximum in the pass band near said cutoff frequencies, a second component filter having predetermined cutoff frequencies outside the pass band of said first component filter and a predetermined frequency time-delay characteristic which is minimum in the vicinity of the cutoff frequencies of said first component filter, said second component filter being coupled in cascade with said first component filter, the reactive constants of said component filters being so proportioned that said time-delay characteristics are complementary over the band of frequencies passed by said composite filter, whereby said first component filter determines the pass band of said component filter and said second component filter is effective to provide an appreciable phase correction near the cutoff frequencies of said first component filter.

HAROLD A. WHEELER.