

[54] PHASE EQUALIZED FILTER

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[52] U.S. Cl. **333/73 W; 333/31 A; 333/83 R**

[51] Int. Cl. **H01p 5/04; H01p 7/06; H03h 7/08**

[58] Field of Search **333/31 R, 73 R, 73 S, 73 W, 333/83 R, 70 S, 82 R, 82 B, 31 A**

[56] References Cited

UNITED STATES PATENTS

2,749,523	6/1956	Dishal	333/83 R
3,597,709	8/1971	Rhodes	333/73 R

3,737,816 6/1973 Honicke..... 333/73 W

Primary Examiner—James W. Lawrence

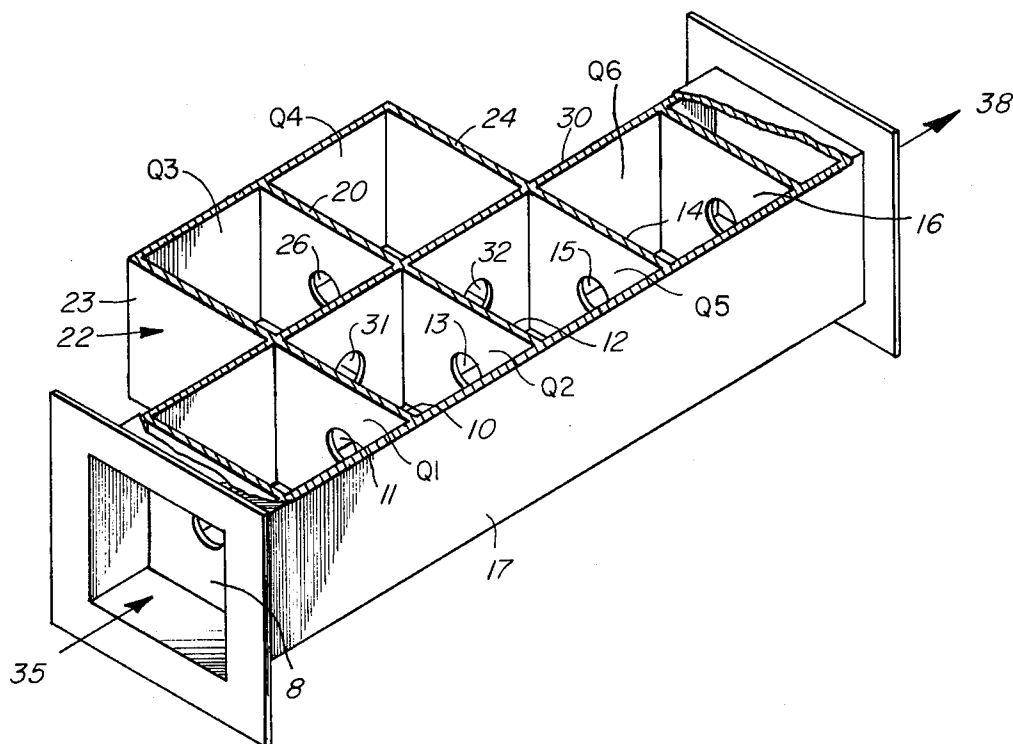
Assistant Examiner—Marvin Nussbaum

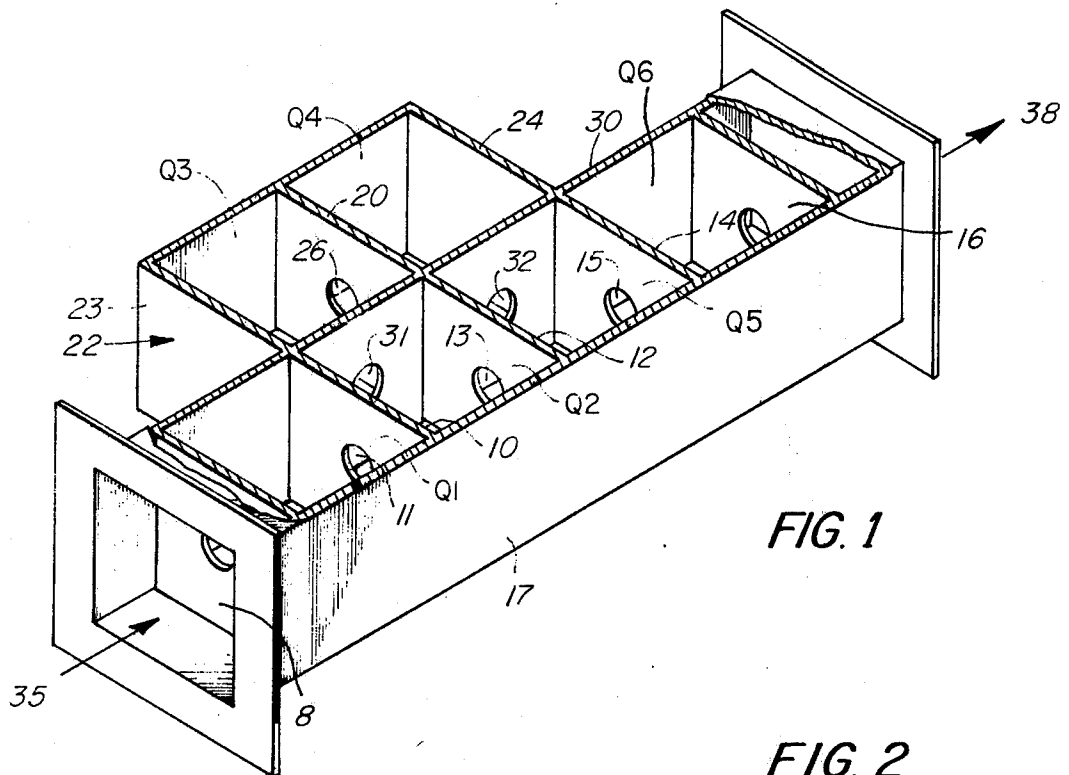
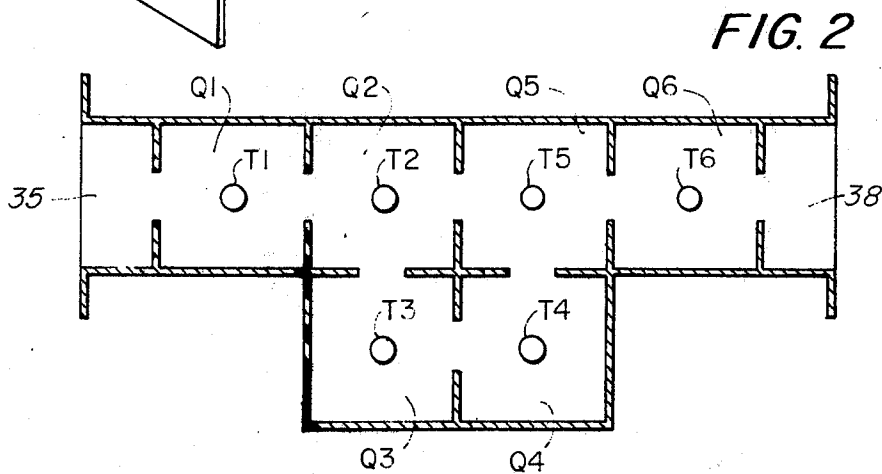
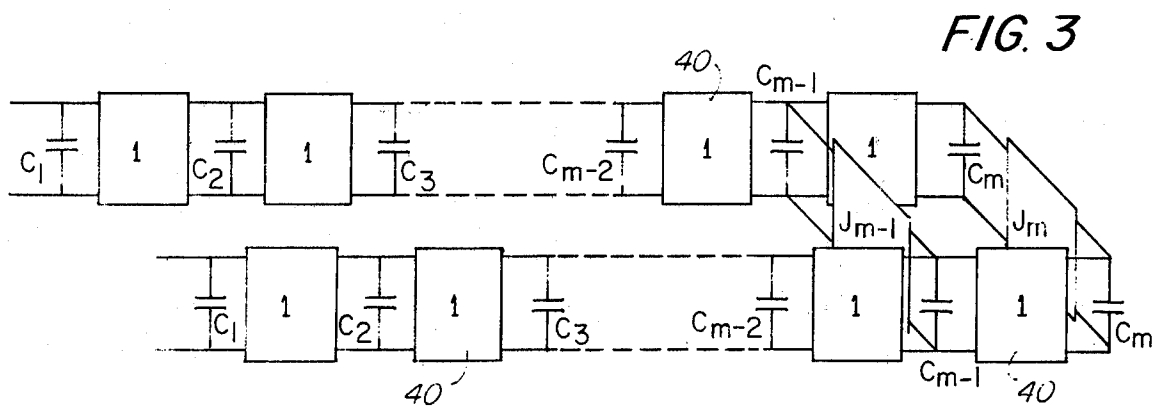
Attorney, Agent, or Firm—Wolf, Greenfield & Sacks

[57] ABSTRACT

The band-pass filter is constructed from a group of direct-coupled resonant elements forming resonant cavities arranged in consecutive order, and at least one alternative path formed by a cross coupling. The filter comprises a first array or series of a plurality of intercoupled resonant cavities having an input end and an output end, and a second array or series of fewer resonant cavities intercoupled with the cavities of the first array. This arrangement provides a band-pass filter having a flat group delay and linear phase over the central portion of the pass band.

11 Claims, 6 Drawing Figures





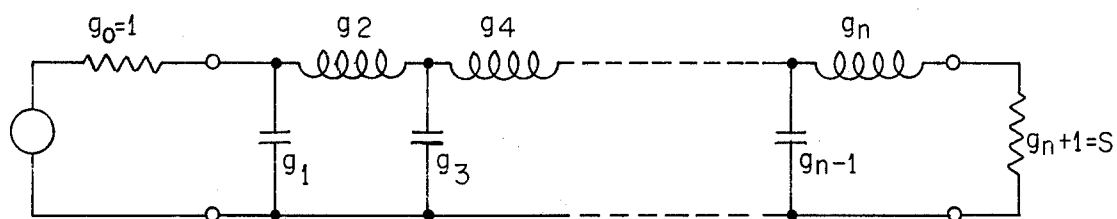


FIG. 4

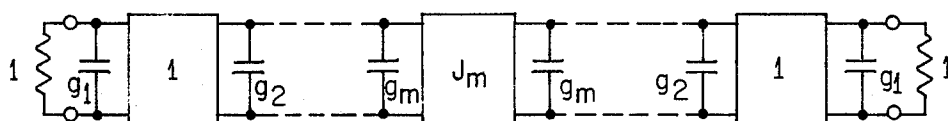


FIG. 5

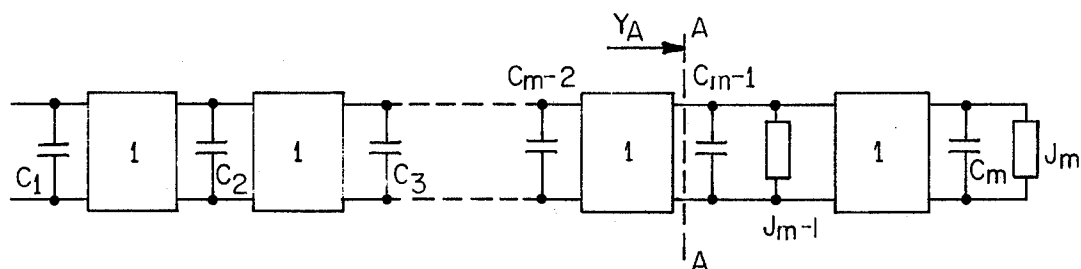


FIG. 6

PHASE EQUALIZED FILTER

FIELD OF THE INVENTION

This invention relates in general to frequency selective apparatus for filtering electro-magnetic energy. More particularly, this invention pertains to a band-pass filter characterized by linear phase over a central portion of the pass-band. In comparison to a simple direct-coupled resonator filter, the filter of the present invention is characterized by a flattened pass-band attenuation and a doubling of group delay band-width.

BACKGROUND OF THE INVENTION

The simple type of direct-coupled resonator filter typically may comprise a series of inter-connected resonant elements. The electro-magnetic wave energy passes by way of one path from the input to the output of the filter; that is apart from multiple reflections that may occur. This type of a filter provides minimum phase linearity and is characterized by phase and delay characteristics which are completely prescribed by the amplitude characteristic.

A filter having both direct and cross-coupled resonators is disclosed in U.S. Pat. No. 3,597,709. In comparison with the simple direct coupled filter, the filter shown in this patent is provided with a plurality of extra cross-coupling paths. Hence, the electro-magnetic wave can reach the output from the input via multiple alternate routes. A filter of this type, as discussed in U.S. Pat. No. 3,597,709, may be designed to provide a wide variety of characteristics, e.g., maximally-flat or equiripple group delay.

One of the primary disadvantages associated with filters of the type shown in U.S. Pat. No. 3,597,709 is that the direct and cross-coupling coefficients between resonators must generally be very close to the theoretical values if a satisfactory performance is to be achieved. This means that a filter with two or more extra cross-couplings may be difficult to tune and consequently quite expensive to produce. In particular, it may be quite difficult to tune a narrow-band filter of this type over a broad frequency band, as required for economic design of filters for communications systems, for example. Another disadvantage associated with these prior art direct and cross-coupled filters is that the out-of-band attenuation is considerably reduced by the presence of the extra cross-couplings. Hence, a greater number of cavities are required than for a conventional coupled filter. This in turn increases the insertion loss in the pass-band of the filter. For cases where between 60% and 100% of the pass-band is required to have a linear phase then a filter of the type described in U.S. Pat. No. 3,597,709 is most desirable. However, there are many applications wherein only the central 50% of the pass-band is required to have linear phase. For example, this is the case in most communication links where flat delay over the central 50 percent of the pass-band may result in major improvements in systems performance since most of the energy is transmitted in the central region of the pass-band.

Accordingly, it is an object of the present invention to provide a band-pass filter of the direct-coupled type preferably having one extra cross-coupling added to the direct coupled resonator filter. This arrangement provides an extremely flat group delay; e.g., about 0.3 nano-seconds variation in the central 50 percent of the pass-band (defined to the equi-ripple points) of a filter

having an absolute group delay on the order of 50 nano-seconds.

SUMMARY OF THE INVENTION

To accomplish the foregoing and other objects of this invention there is provided a band-pass filter which generally comprises a first series of resonant elements, a means for coupling an input signal to a resonant element of the first series, means coupling to a resonant element in the first series for obtaining an output signal and a second series of resonant elements smaller in number than the first series and arranged with each resonant element opposite and in substantial alignment with a different resonant element in the first series. The second series of resonant elements preferably numbers two and provides a single cross-coupling alternate path. The resonant elements in both the first and second series are directly coupled in consecutive order. The means for coupling an input signal is disposed preferably at one end of the first series and the output signal is obtained at the other end of the first series.

In one embodiment of the invention the first series of resonant elements is defined by a waveguide structure partitioned off by iris-defining plates. The second series of resonant elements includes two resonant cavities separated by an iris-defining plate and intercoupled to corresponding resonant cavities of the first series by means of an iris. In addition to the use of a rectangular waveguide the concepts of the present invention may also be applied with circular cavities, coaxial cavities, or with interdigital, comb-line, or helical-line resonators.

BRIEF DESCRIPTION OF THE DRAWINGS

Numerous other objects, features and advantages of the invention will now become apparent upon a reading of the following detailed description taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a perspective view of one form of a filter constructed in accordance with the principles of the present invention;

FIG. 2 is a cross-sectional view of the filter shown in FIG. 1 and including the tuning screws;

FIG. 3 is a low-pass prototype network of the filter shown in FIGS. 1 and 2;

FIG. 4 is a circuit representation of the low-pass prototype for an even-ordered Chebyshev filter;

FIG. 5 is another circuit representation similar to that shown in FIG. 4 for the admittance-inverter form of the Chebyshev low-pass prototype; and

FIG. 6 shows the even mode form of the low-pass prototype network shown in FIG. 5.

DETAILED DESCRIPTION

FIG. 1 is a perspective view of one embodiment of a filter constructed in accordance with the principles of the present invention and partially cut-away to expose the structure of the interior of the filter. This is an embodiment in which the resonant cavities are formed by a sequence of irises located within a hollow rectangular waveguide. A first serial array of resonant cavities Q1, Q2, Q5, and Q6 is formed by the iris plates 8,10,12,14 & 16. The iris plates are spaced along the hollow rectangular waveguide 17 and partition the hollow rectangular waveguide into a tandem sequence of resonant chambers.

A second array of resonant cavities Q3 and Q4 is similarly formed by the iris plate 20 in the hollow rectangular waveguide section 22. The waveguide section 22 is closed at both ends by plates 23 and 24, and the plate 20 has an aperture 26 providing direct coupling between the resonant cavities Q3 and Q4. The waveguides 16 and 22 are separated longitudinally by a common narrow wall 30. The resonant cavities Q2 and Q5 are disposed opposite the respective cavities Q3 and Q4. Coupling between these opposite resonant cavities in the two arrays is provided by coupling apertures 31 and 32 in the common wall 30. Signal energy is coupled into the filter at port 35 of waveguide 16 and the output of the filter is obtained at the output port 38 associated with the other end of waveguide 17. The main path taken by the signal through the filter is sequentially through cavities Q1, Q2, Q3, Q4, Q5, & Q6, but a cross coupling is provided between cavities Q2 and Q5 by means of iris plate 13.

FIG. 2 is a cross-sectional view of the filter of FIG. 1 and also including the tuning screws that may be associated with each cavity of the filter. Regarding the filter shown in FIGS. 1 and 2 the extra cross-coupling may be considered as existing between resonant cavities Q2 and Q5. The filter of the present invention is actually only slightly more complicated than the conventional direct-coupled filter and is easily tuned to any frequency range. Another advantageous feature of the present invention is that the extra cross-coupling between cavities Q2 and Q5 may be made variable by a tuning screw or other means. In FIG. 2 each of the cavities Q1-Q6 have associated therewith respective tuning screws T1-T6. When the cross-coupling between cavities Q2 and Q5 is changed, the filter may be rematched by tuning the main coupling between cavities Q3 and Q4, followed by minor adjustments to the tuning of the adjacent resonant cavities which should have been disturbed only slightly. If the cross-coupling is tightened, then the main coupling by way of cavities Q3 and Q4 is to be loosened. The theory of the present invention which is discussed in more detail hereinafter, shows that the sum of these two couplings remains almost constant. Hence, it is relatively simple to tune the filter to give group delay characteristics which are either undercoupled, critically-coupled, or over-coupled. This is a useful feature for many systems applications of the present invention.

Regarding the embodiment shown in FIGS. 1 and 2, since only one extra cross-coupling is used therein, the out-of-band attenuation is not reduced as much as in the case of the filter of the type shown in U.S. Pat. No. 3,597,709. It can be seen from FIG. 1 that the out-of-band attenuation of an n -cavity filter cannot be worse than that of an $(n-2)$ -cavity conventional filter as disclosed in the prior art patent referred to herein. In fact, since the coupling between cavities Q2 and Q5 is very loose, then the attenuation will be higher than that of an $(n-2)$ -cavity conventional filter.

The insertion loss at mid-band with the filter of the present invention is increased in comparison with that of the conventional direct and cross-coupled filter. At the same time, however, the insertion loss is relatively flattened over the central 50% of the pass-band corresponding to the flat group delay band-width. Typically, for an insertion loss of one dB this insertion loss is constant to within 0.05 dB over the central 50 percent of the pass-band. Although the mid-band insertion loss of

the filter is perhaps 0.3 dB higher than the conventional filter, the attenuation at the edges of the central 50% is increased by a rather small amount. In effect, the extra cross-coupling causes the insertion loss characteristic to flatten by increasing the mid-band loss to equal the loss at the 50 percent frequencies.

Having described a waveguide embodiment of the present invention, consideration is now given to the theory and design of the structure.

THEORY AND DESIGN PROCEDURE

In U.S. Pat. No. 3,597,709 a design procedure was disclosed relating to the filter structure disclosed therein for a band-pass filter. The theory of the present invention is examined using a low-pass prototype lumped constant embodiment as depicted in FIG. 3. The extra cross-coupling is represented by the admittance inverter J_{m-1} .

The transfer function of the low-pass prototype takes the form:

$$S_{12}(p) = \frac{p^2 - \sigma_1^2}{D_n(p)} \quad (1)$$

where p is the complex frequency variable, $D_n(p)$ is a Hurwitz polynomial, and σ_1 is a positive parameter. Transmission zeros are located on the real axis at $p = \pm \sigma_1$ i.e., the amplitude response is controlled mainly by the denominator polynomial, and the phase equalization is equivalent to a single Darlington C-section. The network shown in FIG. 3 is an $n=2m$ ordered low-pass prototype network wherein n = the number of cavities. The network includes n shunt capacitors $C_1, C_2, \dots, C_{m-1}, C_m$ spaced by $(n-1)$ ideal admittance inverters indicated generally by the reference character 40. There are a plurality of admittance inverters, shown in FIG. 3 along the main path, represented by a unity value. The inverter J_m is also considered as in the main path and the inverter J_{m-1} represents the one extra cross-coupling path.

This low-pass prototype network will now be derived by a modification of the standard lumped-element even-ordered Chebyshev low-pass prototype filter. See IEEE Transactions on Microwave Theory and Techniques, Volume MTT-18, Number 6, June, 1970, pp.290-301 by John David Rhodes. The n^{th} ordered prototype is shown in FIG. 4, where the element values are given by:

$$\begin{aligned} g_0 &= 1 \\ g_1 &= 2 \sin \left(\frac{2r-1}{2n} \pi \right) / \gamma \\ g_r g_{r+1} &= \frac{4 \sin \frac{2r-1}{2n} \pi \sin \left(\frac{2r+1}{2n} \pi \right)}{\gamma^2 + \sin^2 \left(\frac{r\pi}{n} \right)} \\ \text{Where } (r &= 1, 2, \dots, n-1) \\ g_{n+1} &= S \\ \text{and} \\ \gamma &= \sinh \left(\frac{1}{n} \sinh^{-1} \frac{2\sqrt{S}}{S-1} \right) \end{aligned} \quad (2)$$

S is the VSWR at d.c., or the ratio of the output conductance to the input conductance.

Using the relationship:

$$g_r g_{r+1} = g_{n-r} g_{n-r+1} \quad \text{where } (r = 0, 1, 2, \dots, n) \quad (3)$$

then it is possible to transform the circuit of FIG. 4 to the physically symmetric circuit of FIG. 5 by introducing ideal admittance inverters. Electrically, this network is actually antimetric. The central admittance inverter is given by:

$$J'_m = \frac{\sqrt{S}}{1/\sqrt{S}} \begin{matrix} m \text{ odd} \\ M \text{ even} \end{matrix} \quad (4)$$

This circuit is seen to be identical to that of FIG. 3 with the exception of the extra cross-coupling admittance inverter J_{m-1} . In accordance with the theory of this invention, the inverter J_{m-1} , is now introduced in the form of a small perturbation of the Chebyshev filter (it is quite small in practice). The even-mode embodiment of the network of FIG. 3 formed by inserting an open-circuit along the physical line of symmetry is shown in FIG. 6. The only portion of the network which is changed from the Chebyshev values is to the right of plane A—A. The admittance at this plane is:

$$Y_A = j \left[\omega C_{m-1} + J_{m-1} - \frac{1}{\omega C_m + J_m} \right] \quad (5)$$

In the Chebyshev case $J_{m-1} = 0$, and the admittance is

$$Y'_A = j \left[\omega C_{m-1} - \frac{1}{\omega C_m + J'_m} \right] \quad (6)$$

It has been found that for a reasonably small value of J_{m-1} then a very good well matched linear phase filter may be designed by setting $Y_A = Y'_A$ at $\omega = \omega_0$. This gives the relationship

$$J_m = \frac{J'_m}{1 + J'_m J_{m-1}} \quad (7)$$

and since $J'_m \approx 1$ and J_{m-1} is small, there results the following approximate equation:

$$J_m + J_{m-1} \approx J'_m$$

The low-pass prototype is designed, therefore, by introducing a finite value of J_{m-1} into the Chebyshev prototype, adjusting J_m from its Chebyshev value J'_m given by equation (4), using equation (7), and analysing the filter over the low pass-band. It is then a simple matter to find a value of J_m giving the desired group delay response since only one parameter is varied. It is found that under-coupled, critically-coupled, or overcoupled group delay characteristics may be obtained.

The band pass filter is derived from the low pass prototype using any of the methods described in the literature. See, for examples, other articles by J. D. Rhodes appearing in the June 1970 issue of the IEEE Transactions Vol. Mtt-18 and entitled "The generalized interdigital linear phase filter" pp. 301-307, and "The generalized direct-coupled-cavity linear phase filter" pp. 308-313.

It should be evident from the following description that the invention can be embodied in many different forms. It is preferred to use only one cross-coupling path, however, especially for filters containing a number of cavities, two or more cross-coupling paths can be employed.

Because the invention can be embodied in varied structures, it is not intended that the invention be limited to the forms here illustrated or described. Rather, it is intended that the invention be limited solely by the appended claims and include those structures that do not fairly depart from the essence of the invention.

What is claimed is:

1. A microwave band-pass filter having a relatively flat group delay and linear phase over the central portion of the pass-band, said filter comprising;
 - means defining a first series of resonant elements, means for coupling an input signal to a resonant element of the first series, the resonant elements in the first series being each directly coupled in consecutive order with its adjacent element,
 - means defining a second series of resonant elements smaller in number than the number comprising said first series and arranged with each resonant element opposite and in substantial alignment with a different resonant element in the first series, means coupling from a last resonant element in the first series for obtaining an output signal therefrom, the resonant elements in the second series being each directly coupled in consecutive order with its adjacent element,
 - said first and second series being arranged to provide a main path through all of said resonant elements with at least one cross-coupling path being provided between two adjacent elements of the first series,
 - means for independently tuning each resonant element, and
 - tuning means associated with said one extra cross-coupling path.
2. The filter of claim 1 wherein both the first and second series of resonant elements each include a waveguide structure partitioned by at least one iris-defining means to form a plurality of resonant cavities.
3. The filter of claim 2 wherein said waveguide structures have a common wall having means defining at least two coupling apertures between said first and second series.
4. The filter of claim 1 wherein said second series includes only two resonant elements and there is provided only one cross-coupling path.
5. The filter of claim 1 characterized by a flat group delay over approximately the center 50 percent of the pass band.
6. The filter of claim 5 including means for independently tuning each resonant element.
7. A microwave band-pass filter having a relatively flat group delay and linear phase over the central portion of the pass band, said filter comprising;
 - means defining a series of resonant elements including a waveguide structure partitioned by a plurality of iris-defining means to form a plurality of resonant cavities,
 - said series of resonant elements being arranged so that at least two of said elements are opposite and in substantial alignment with other resonant elements of the series to define a main path through all of the resonant elements,
 - two other of said elements providing one cross-coupling path,
 - means for independently tuning each resonant element,

first means for tuning the coupling between the said at least two resonant elements,
and second means for tuning the coupling between the said two other resonant elements,
said first and second tuning means operable to provide group delay characteristics which are either undercoupled, critically-coupled or over-coupled.

8. The filter of claim 7 wherein there is provided only one cross-coupling path.

9. The filter of claim 7 wherein all of said resonant elements are coupled in line except said at least two

resonant elements.

10. The filter of claim 9 wherein a first of said resonant elements of the in line group includes means for receiving an input signal and a last of said resonant elements of the in line group includes means for coupling out an output signal.

11. The filter of claim 10 wherein said at least two resonant elements are opposite any other resonant elements except said first and last resonant elements.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,882,434 Dated May 6, 1975

Inventor(s) Ralph Levy

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 4, line 18, change "J_{m-1}" to --J_{m-1}--.

Column 4, equation 1 should read --

$$S_{12}(p) = \frac{p^2 - \tilde{\sigma}_1^2}{D_n(p)} \quad --$$

Column 4, line 34, change "C_{m-1}" to --C_{m-1}--.

Column 4, line 39, change "J_{m-1}" to --J_{m-1}--.

Column 4, line 53, delete the second "n" appearing in the lower part of the equation in the parentheses.

Column 4, line 55, draw a line -- above
y² + sin²....

Column 4, line 60, change the first occurrence of "sink" to --sinh--.

Column 4, line 60, change the second occurrence of "sink" to --sinh--.

Column 5, line 9, change "M even" to --m even--.

Signed and Sealed this

twentieth Day of April 1976

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks