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[54] **PLURAL CAVITY BANDPASS WAVEGUIDE FILTER**

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[52] **U.S. Cl.** ....**333/21 A,** 333/73 W

[51] **Int. Cl.**........**H01p 1/16,** H01p 7/06, H03h 13/00

[58] **Field of Search** ....333/73, 73 C, 73 W

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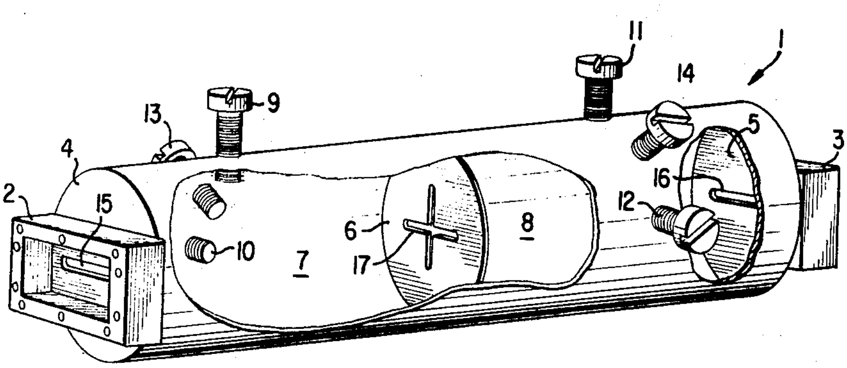
[57] **ABSTRACT**

A waveguide filter having two cascaded double-tuned cavities which are resonant in two independent orthogonal modes and provide a bandpass response. An elliptic function is obtained from the bandpass microwave filter structure by using a direct-coupling iris which selectively couples identical resonant modes between adjacent cavities.

14 Claims, 5 Drawing Figures



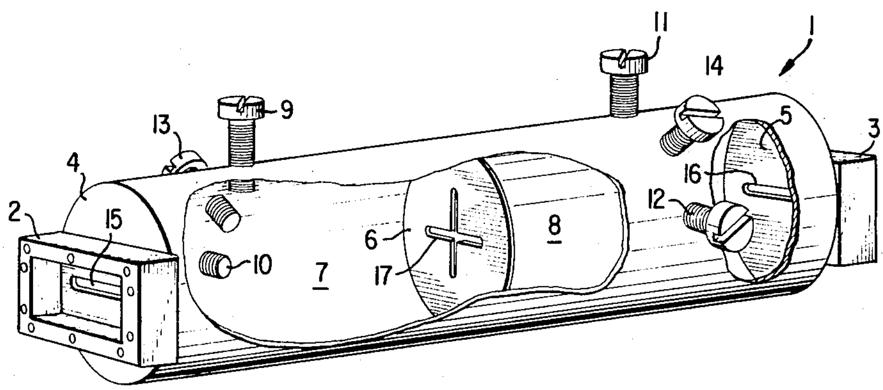
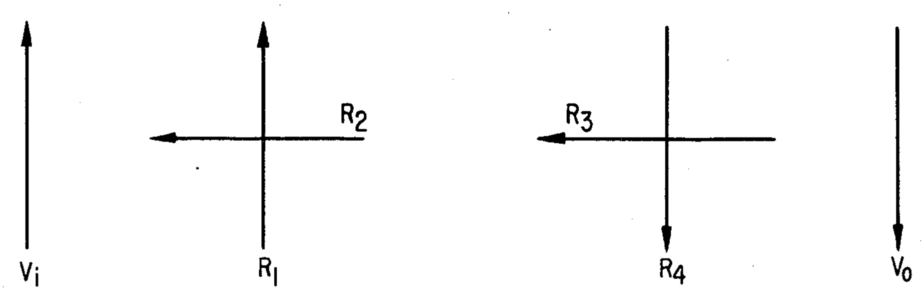


FIG. 1a

FIG. 1b



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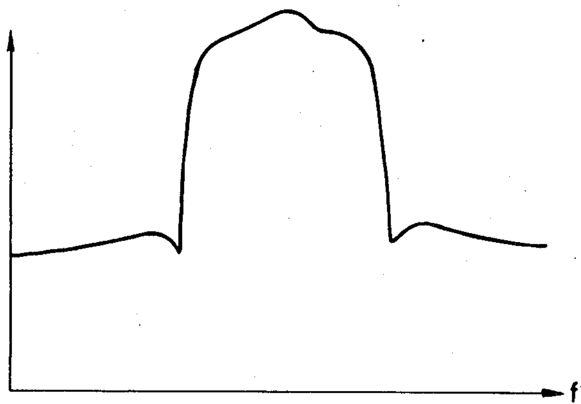

FIG. 3

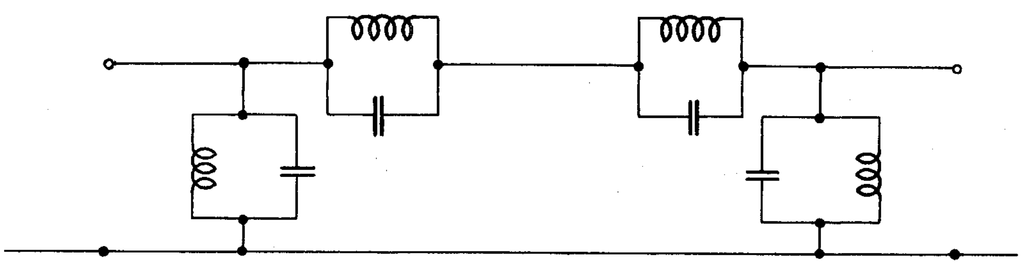

FIG. 2a

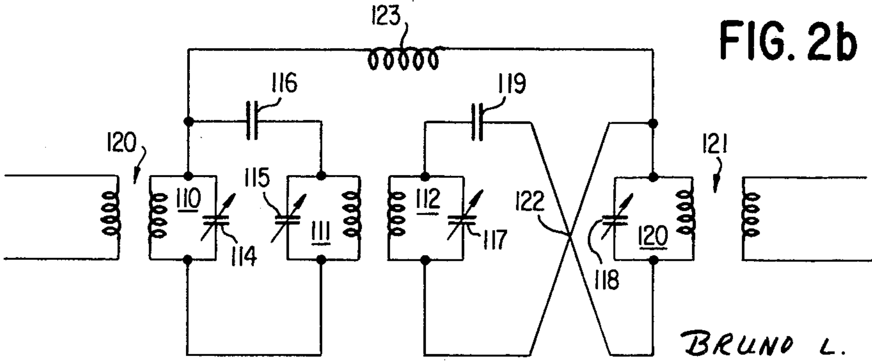

FIG. 2b

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PLURAL CAVITY BANDPASS WAVEGUIDE FILTER

BACKGROUND OF THE INVENTION

The subject matter of the present invention is generally concerned with the use of plural double-tuned resonant cavities to approximate the behavior of complex lumped element microwave filters. More particularly, the invention is a bandpass microwave filter including a plurality of coupled resonant cavities, each of which is tuned to support more than one independent mode of propagation at frequencies within a given pass band. A plurality of irises selectively couple propagating modes in each resonant cavity.

Bandpass filters which are simple, light weight and effective in the microwave region of the frequency spectrum remain in the early stages of development. It is well known that conventional lumped circuit series or parallel resonant elements are impractical in the microwave region because of substantial radiation losses due to the high current densities present at these frequencies. The difficulties in constructing inductances and capacitances having the dimensions required to provide the pass band at a microwave center frequency add to the undesirability of conventional circuitry.

It is well known that at frequencies above a particular cutoff frequency it is possible to achieve propagation of a wave through a microwave transmission medium. The medium is typically a hollow element of circular, rectangular or a square cross section which guides the propagating wave from one point to another with a minimum of distortion and attenuation. The wave transmitted down such a waveguide will typically have a single polarization. However, depending upon the shape of a cross section of the waveguide, the wave may propagate with more than one polarization. Should the wave be confined to a particular length of waveguide it may oscillate at its natural resonant frequencies in more than one mode. A cavity, defined by this length of waveguide, will behave like a conventional resonant circuit and can provide a filtering function equivalent to the lumped element resonant circuit.

Since the single cavity filter may not provide sufficient off-band attenuation to give the desired frequency selectivity, a plural cavity design can be used to provide this selectivity. The plurality of cavities may be directly coupled together as a series of resonant elements by quarter wavelengths of transmission line whose dimensions are selected to effectively transmit a resonant signal at the center frequency.

Waveguide filters embodying these principles have been proposed and are able to provide the maximally flat type of response or the Tchybycheff type of response readily available from conventional circuitry at low frequencies. The elliptic type filter response, exhibiting an extremely steep rejecting characteristic, has also been known in microwave technology. However, the microwave implementation of these types of filter rejection characteristics has resulted in extremely complex, bulky and heavy structures as seen in "Narrow Bandwidth Elliptic Function Filters", IEEE Transactions Microwave Theory and Technique, Volume 17, No. 12, December 1969 at page 1,108. These dimensional limitations are incompatible with spacecraft or other size or weight limited environments.

A cavity may resonate in more than one independent mode at its natural frequencies. The modes resonating in a waveguide cavity may have an orthogonal orientation, that is, a vertical polarization and a horizontal polarization. By definition two modes which are orthogonal are separated by a 90° difference in polarization and will not experience any mutual interference.

The theory behind single mode filters in waveguides is equally applicable to the dual-mode case in which two orthogonal modes independently resonate in a single cavity. It has been shown by George Ragen in *Microwave Transmission Circuits* (**1964**) on page **673** that a single cavity may behave like a two cavity filter. By coupling one of the orthogonal modes to the other orthogonal mode the dual-mode effect may be achieved, provided that each independent mode is properly tuned to the resonant frequency of the desired signal. It follows that if the resonant frequencies of a dual-mode cavity and the coupling between its different modes are adjusted to coincide with the corresponding quantities for a lumped element filter, the behavior of the filter will be approximated by the cavity over a limited frequency band.

Although the use of the dual mode in a single resonant cavity has been known in the prior art, the synthesis of filter response curves based upon plurality of dual-mode cavities has not been taught by the prior art. Furthermore, the selective coupling of identical modes between a plurality of cavities resonating with orthogonal modes has not previously been considered.

SUMMARY OF THE INVENTION

The present invention provides a lighter, more compact structure for achieving the bandpass response functions discussed above. The invention uses N physical waveguide cavities which resonate in two independent orthogonal modes and are coupled together to provide the filtering capacity of 2N cavities resonating in a single mode. The coupling is provided by structural discontinuities within the physical cavity. The discontinuity may be a screw mounted in the cavity wall.

One feature of the invention is the use of selective polarization discriminating couplings between the N cavities to transfer energy between identical modes in the coupled cavities. The selective couplings may be polarization discriminating irises, transmission lines or microwave bridge elements.

A further feature of the invention is the use of a phase inversion means in coupled cavities to provide a subtraction capability between identical modes in the coupled cavities. This subtraction capability can provide steep response skirts for the pass band of a filter.

DESCRIPTION OF THE DRAWINGS

FIG. 1*a* illustrates a filter configuration having two resonant cavities and embodying the principles of the present invention.

FIG. 1*b* is a drawing of the different electrical field polarizations along the length of the filter shown in FIG. 1*a*.

FIG. 2*a* is a drawing of a typical lumped element π network which at low frequencies provides the elliptical function response.

FIG. 2*b* is a drawing of a circuit which is equivalent to the circuit in FIG. 2*a* and is a lumped circuit realization of microwave structure of FIG. 1*a*.

FIG. 3 is an illustration of the typical elliptic function response.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring at this point to the drawings, FIG. 1*a* illustrates a preferred embodiment of the invention which defines the fundamental principles that distinguish the invention from the prior art. A circular waveguide section **1**, which may be typically coupled to a rectangular waveguide at joints **2** and **3**, is limited at both ends by reflective plates **4** and **5**. The circular section is divided by a third reflective plate **6** which defines two physical cavities **7** and **8**. Since, in general, frequency is inversely proportional to wavelength (λ) and the resonant frequency of a cavity is proportional to its length, selectivity at the desired center frequency requires that each of the filter's physical cavities be typically λ/2 in length. Each physical cavity is capable of resonating in two independent orthogonal modes at the center frequency of the usable bandwidth of the waveguide. The principles applicable to this type of circular waveguide filter operating in the H_{111} mode may obviously be extended to waveguides having square, rectangular or elliptical cross sections which are capable of supporting two or more independent modes at a resonant frequency. However, the circular waveguide filter is preferred due to its better selectivity, lower insertion losses and smaller weight.

The polarization of the resonant orthogonal modes is conventionally defined by horizontal and vertical vectors as shown in FIG. 1*b* which are independent of each other and can propagate within the cavity without interference. If the cavity has perfect symmetry and proper dimensions, both modes will propagate at the same frequency. However, this structural condition is not obtainable in practice, and it is convenient to provide two tuning screws, symmetrically inserted into the cavity along radii which are coincident with the horizontal and vertical vectors of the orthogonal modes, to permit the independent tuning of both modes to the same desired frequency. Tuning screws **9** and **10** are placed in the walls of the first cylindrical cavity **7** to provide a capacitive tuning capacity for the cavity over a portion of the frequency band in the respective vertical and horizontal modes. Tuning screws **11** and **12** are similarly mounted in the walls of cavity **8** to provide a capacitive tuning capacity. All fundamental modes propagating in the filter may thereby be tuned to the same desired frequency. These tuning screws are normally placed at the center of the cavity at a distance of approximately (λ/4), where electric fields are a maximum and the action of the screws is most effective, and where currents are at a minimum and negligible additional losses are introduced.

Coupling screws **13** and **14** are also mounted into the wall of each of the respective cavities **7** and **8** at the center of the cavity where electric fields are at a maximum. Each screw **13** and **14** provides a means, inside the cavity, which is capable of coupling the electric field from one of the independent orthogonal modes to the other. The screws are oriented along a radius at a 45° angle to the fundamental orthogonal mode vectors to insure maximum coupling from one mode to the other and to provide an identical effect on the frequency of both modes.

It should be obvious from vector analysis that by changing the radial angle of the coupling screw within the cavity, the amount of power transferred from one mode to the other mode will vary as a sinusoidal function of the radial angle. For example, as the radial angle of screw **13** is shifted in the clock-wise direction, about the center axis of the waveguide, the amount of coupling goes to zero when the screw is coincident with the vertical mode. A displacement of screw **13** by 90° from the illustrated position will also result in a maximum coupling, but phase shifted by 180°; the couplings will be equal in magnitude but opposite in sign.

Coupling screw **14** is mounted in cavity **8** at an angle of 45° between the two orthogonal modes and is shifted by 90° from the radial orientation of screw **13**. The coupling provided by screw **14** is, therefore, equal to the coupling provided by screw **13** but of opposite sign. As will be shown below, this difference of sign in the two cavities is necessary to achieve the elliptic function response of the filter.

It is not desirable, as a practical matter, to use a coupling screw mounted in a radial direction other than at a 45° angle to the orthogonal mode vectors since the screw would affect the frequency of each orthogonal mode by a different amount and therefore complicate tuning of the two modes by the tuning screws. Since the amount of coupling from one mode to another also depends upon the length of the capacitive coupling structure in the cavity, the degree of coupling is preferably adjusted by varying the length of the coupling screw which extends into the cavity. As is well known in the art, the capacitive coupling effect may also be provided by any equivalent structural discontinuity within the cavity such as a dielectric rod or dent in the waveguide wall.

An input slot or iris **15** and an output slot or iris **16** are provided in the reflective plates **4** and **5** and couple the polarized transmitted wave in a rectangular waveguide to the waveguide filter. Since the wave propagating in a rectangular waveguide is normally polarized in only one direction, a discriminating coupling at the input to the filter is not necessary. FIG. 1*b* illustrates a vector representation of the input wave V_i and the output wave V_o which are assumed to have a vertical polarization in the rectangular waveguide of the preferred embodiment. Propagation within the cavities **7** and **8** is, however, in the cross polarized mode and reflection of the coupled, horizontal mode at plates **4** and **5** without transmission to the rectangular waveguide is necessary to support resonance in the dual mode.

The geometry and orientation of the coupling slots **15** and **16** are selected to maximize coupling of any incoming and outgoing waves having the proper polarization, but to minimize coupling of other polarizations and to confine the opposite component of the resonating cross polarized waves within cavities **7** and **8**. Geometrically, in this particular case, the irises are rectangular slots which are narrow with respect to their length to achieve good polarization discrimination. The slots are oriented in the waveguide to pass the vertically polarized input and output waves but to reflect the horizontal component of the resonant cross polarized mode within the cavities. Accordingly, the slot lengths are positioned to be normal to the vertically polarized mode and parallel to the horizontally polarized mode.

It should be obvious to one of ordinary skill in the art that the input structure need not be limited to a rectangular waveguide which transmits waves having a single polarization. Any other kind of transmission line may be used which propagates signals having one or more modes, provided that adequate polarization discriminating coupling at the input is achieved. In addition, other geometries and orientations of the coupling structure at the input and output to the filter may be selected to pass waves having a desired polarization into and out of the resonant cavities and to reflect the undesired components of the orthogonally polarized waves within the cavities.

A third iris **17**, located in plate **6** which is transposed transversely in the cylindrical waveguide section **1**, inductively couples the two physical cavities **7** and **8**. This iris has, typically, a geometrical configuration and an orientation which will selectively couple each of the orthogonal modes resonating in the cavities **7** and **8**. As will be explained below, in order to achieve the elliptic function it is necessary that the horizontal mode propagating in resonant cavity **7** be maximally coupled to the horizontal mode propagating in resonant cavity **8** and that some lesser degree of coupling exist between the vertically polarized modes of cavities **7** and **8**.

A unique geometrical configuration is shown in FIG. 1*a* for the iris **17**. The coupling slot can be viewed as two overlapping, horizontal and vertical slots which are symmetrically oriented to coincide with the orthogonal vectors defining the two propagating modes in the respective physical cavities. The dimensions of the slot **17** are selected to provide the desired degree of coupling of the horizontal and the vertical modes. It would be obvious to one of ordinary skill in the art that other coupling means such as quarter wave length lines or additional geometrical configurations for the iris **17** may be used to provide the desired degree of coupling between the horizontal and vertical modes in each of the cavities. As an example, since identical modes in each cavity are coupled together, perfect polarization discrimination is not necessary and rectangular or elliptical shapes giving different degrees of coupling between the two modes may be selected. However, the iris structure illustrated in FIG. 1*a* has been proven to provide the desired independent control over the degree of coupling of the two orthogonal modes.

In order to more fully explain the operation of the present invention, an examination of the electrical field vectors within the cylindrical waveguide filter will now be made by referring once again to FIG. 1*b*. Assuming that the input polarization is vertical, horizontal coupling slot **15** will transmit the vertical mode V_i to resonant cavity **7**. Vector V_i will resonate within cavity **7** as mode vector **R1** and the energy from the vertically polarized wave **R1** will be transferred to the non-interfering horizontally polarized mode **R2** by coupling screw **13**. The horizontal and vertical signals **R1** and **R2** will simultaneously and independently propagate within the cavity **7** in the crossed mode as illustrated. The vertical dimensions of iris **17** are selected to inductively couple the horizontal mode **R2** of the electric field existing in cavity **7** to the cavity **8** as horizontal resonant mode **R3**. Mode **R3** will be coupled to the vertical resonant mode **R4** by coupling screw **14**, resulting in the simultaneous and independent propagation of the crossed modes **R3** and **R4** within cavity **8**. As previously discussed, coupling screw **14** is oriented at a 90° angle to coupling screw **13** and therefore imparts a 180° phase shift to vertical resonant mode **R4** with respect to vertical mode **R1**. As shown in FIG. 1*b*, each of the cavities **7** and **8** have horizontal modes which are identical in phase and magnitude, however, the vertical modes are seen to be 180° out of phase. The horizontal dimension of iris **17** provides a coupling between the vertical mode **R1** in cavity **7** and the vertical mode **R4** in cavity **8**. The coupling of these two modes which are 180° out of phase will provide the desired elliptic function. The coupling of modes **R4** and **R1** is smaller than the coupling of modes **R2** and **R3** and will only cancel the frequency response of the filter at the edges of the pass band resulting in the characteristic steep sides and notches of the elliptic filter response as seen in FIG. 3.

The microwave structure shown in FIG. 1a may be represented by an equivalent lumped element circuit and techniques for converting the functions of a microwave element to a circuit element have been examined in "Microwave Transmission Circuits," Volume 9, MIT Radiation Laboratory Series, pp. 661–706. FIG. 2*a* is a circuit diagram of the classic π section which at low frequencies provides the elliptical function response shown in FIG. 3. FIG. 2*b* is a lumped element filter, derived from the π section of FIG. 2*a*, which by conventional circuit synthesis techniques is equivalent to the light weight microwave structure of the present invention and provides an identical elliptical function response.

The equivalent circuit, illustrated in FIG. 2*b*, consists of four parallel tank circuits connected by two inductive couplings and two capacitive couplings. The first section of the physical cavity **7** resonates in mode **R1** and **R2** and is equivalent to the first resonant parallel circuits **110** and **111** respectively in FIG. 2*b*. Similarly, resonant circuits **112** and **113** are equivalent to the resonant modes **R3** and **R4** present in the second physical cavity. The capacitive tuning screws **9** and **10** are equivalent to the capacitors **114** and **115**. The coupling between vertical mode **R1** of the first physical cavity and horizontal mode **R2** of the first physical cavity is equivalent to the capacitive coupling element **116**. Tuning screws **11** and **12** are equivalent to the capacitors **117** and **118**, while capacitive coupling screw **14** is equivalent to the capacitive coupler **119**. The input and output irises **15** and **16** are inductive devices which are assumed to provide a lossless coupling of the waveguide to the filter; consequently, the two irises are equivalent to perfect transformers **120** and **121** which transfer all power in the input signal to the cavities and from the cavities to the output circuit. Referring at this time to the tank circuit **113** whose resonance is equivalent to resonant mode **R4**, the input from coupling capacitance **119** is inverted in phase by a crossover circuit **122** which is equivalent to the displacement of the coupling screw by 90°. The output of this tank circuit is fed back to the input tank circuit by an inductor **123** which is equivalent to the inductive coupling of mode R4 to mode R1 through the horizontal portion of iris **17**. The feedback of this negative resonant signal to the first resonant circuit provides the steep slope and the notches in the elliptical function response.

From the above discussion it should be obvious to one of ordinary skill in the art that by cascading two cavities resonating in the double mode, the equivalent of a four cavity filter resonating in a single mode will result, accompanied by a substantial reduction in weight. In addition it should be obvious that the principles governing the two-cavity case will apply to N cavities, each operating in a double mode, and that the N double mode cavities will be equivalent to 2N cavities. Filters having an even number of cavities, which embody the present invention, have been realized in the two and four cavity cases. Computer simulation has shown that the invention may be used in filters having an odd number of cavities as well. Furthermore, the interconnection of identical modes in the N cavity case may obviously be accomplished through the irises of cascaded cavities or may conveniently be facilitated by the direct connection of the cavities by polarization discriminating waveguide bridge elements. As is well known in the art the cavities may be in-line or may be folded to achieve a compact filter structure.

Although the preferred embodiment describes structure for achieving an elliptical function response, the fundamental principles of the invention can be used by one of ordinary skill in that art to achieve the normally flat, the Tchybycheff or other quasi-elliptic function responses.

We claim:

1. A plural cavity waveguide filter comprising,
   a. a plurality of waveguide cavities, each resonating at its resonant frequency in a first and a second independent orthogonal mode;
   b. first discontinuity coupling means oriented in each of said cavities for intra coupling said first mode to said second mode;
   c. second coupling means connecting selected ones of said cavities for inter coupling like oriented modes in said selected cavities said second coupling means including polarization discriminating means adapted to provide selective inter coupling between like oriented modes in said cavities.

2. The invention as recited in claim **1** wherein said first coupling means is adaptable to provide either an intra coupling having a first phase or an intra coupling having a second phase differing from said first phase by 180°.

3. The invention as recited in claim **2** wherein said second coupling means includes a reflective plate directly connecting two of said cavities, said plate including an iris for selectively inter coupling the identical modes in said two cavities.

4. The invention as recited in claim **1** wherein said filter includes
   tuning means in each of said cavities for independently tuning each of said modes to the cavity resonant frequency.

5. The invention as recited in claim **4** wherein said second coupling means is a reflective plate having a coupling iris, the dimensions of said iris being selected to provide said selective inter coupling between identical modes.

6. The invention as recited in claim **5** wherein said waveguide cavities are cylindrical waveguide sections and wherein said tuning means includes two adjustable screws mounted in said waveguide sections and coincidently disposed along said independent orthogonal resonant modes.

7. The invention as recited in claim **6** wherein said plurality of cavities include an input and an output cavity, said input cavity being coupled to an input waveguide by a first reflective plate having a polarization discriminating coupling iris, and said output cavity of the filter is connected to an output waveguide by a second reflective plate having a polarization discriminating iris.

8. The invention as recited in claim **1** comprising N physical cavities resonating in said orthogonal modes whereby said filter is equivalent to 2N physical cavities resonating in a single mode.

9. A waveguide filter having an elliptic function response comprising:
   a. a first waveguide cavity resonant in first and second independent orthogonal modes;
   b. a second waveguide cavity resonant in said first and said second independent orthogonal modes;
   c. tuning means in each of said cavities for independently tuning each of said resonant modes to its resonant frequency;
   d. coupling means in said first cavity for capacitively intra coupling said first resonant mode to said second resonant mode;
   e. coupling means in said second cavity for capacitively coupling said first resonant mode to said second resonant mode and for shifting the phase of said second mode by 180° with respect to said first mode of said first cavity;
   f. inductive coupling means for selectively inter coupling said first resonant modes and said second resonant modes in said cavities.

10. An elliptic filter as recited in claim **9** wherein said inductive coupling means physically disposed between said first and said second waveguide cavities.

11. A filter as recited in claim **10** wherein said tuning means comprise two screws, mounted in the wall of each cavity, which are coincident with the vectors of said orthogonal modes.

12. A filter as recited in claim **11** wherein said inductive coupling means is a first reflective plate having a coupling iris whereby the degree of coupling between identical modes in each cavity is selectively adjusted by varying the dimensions of said iris.

13. An elliptic filter as recited in claim **12** wherein said first cavity of the filter is connected to an input waveguide by a second reflective plate having a polarization discriminating coupling iris, and said second cavity of the filter is connected to an output waveguide by a third reflective plate having a polarization discriminating coupling iris.

14. A filter as recited in claim **9** wherein a plurality of said first and second waveguide cavities are connected in cascade and wherein said inductive coupling means includes a first means for directly connecting adjacent cavities and a second means for inter connecting selected cavities.

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