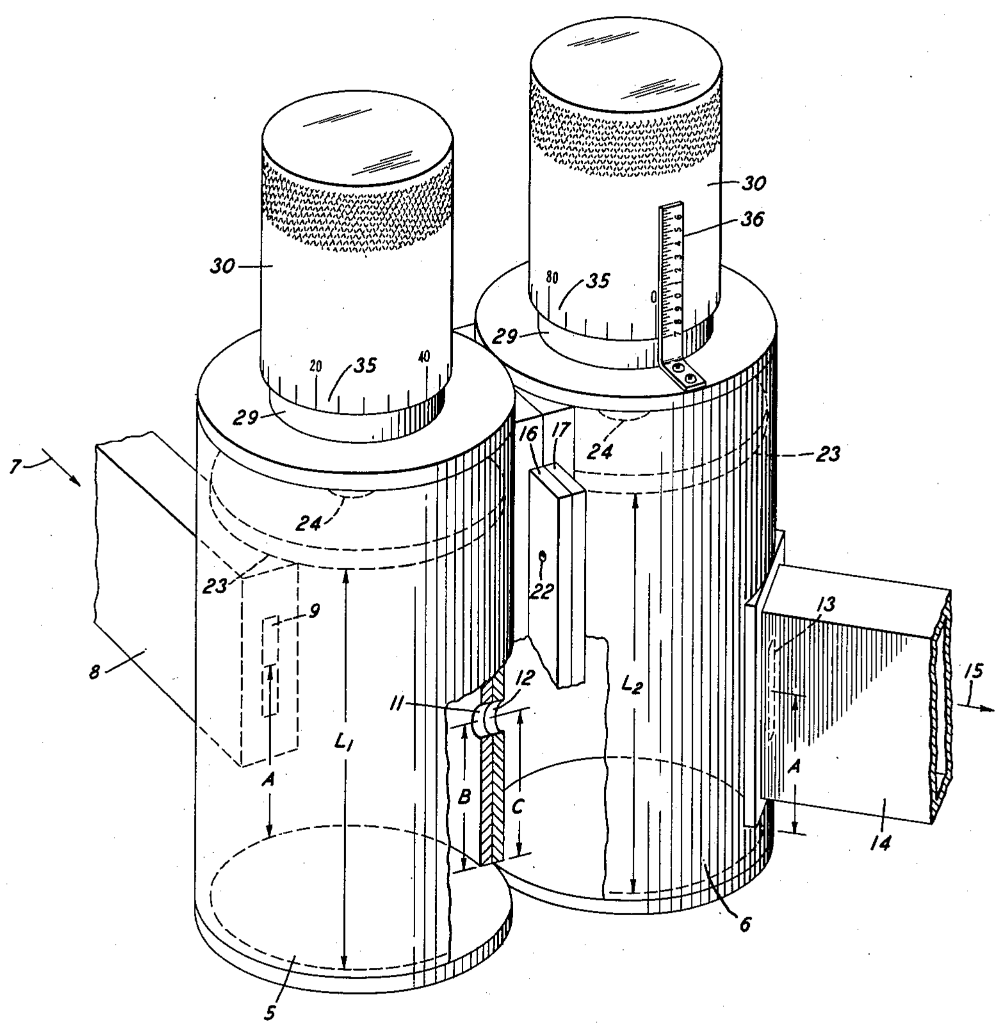
Nov. 9, 1954 J. P. KINZER ET AL 2,694,186

WAVE FILTER

Filed Jan. 4, 1951 2 Sheets-Sheet 1

FIG. 1



INVENTORS: J. P. KINZER
R. W. MARSHALL
I. G. WILSON

BY Ralph T. Holcomb
ATTORNEY

WAVE FILTER

Filed Jan. 4, 1951 2 Sheets-Sheet 2

FIG. 2

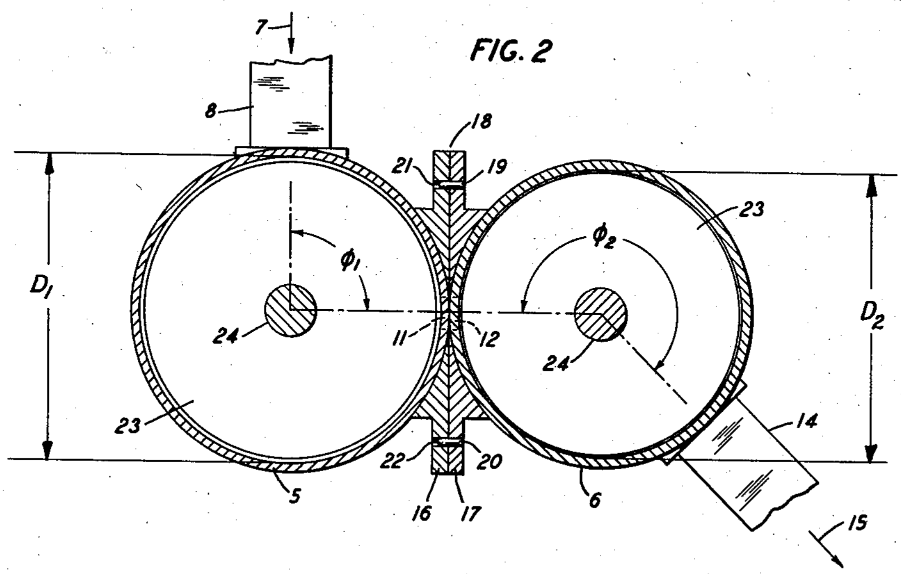


FIG. 3

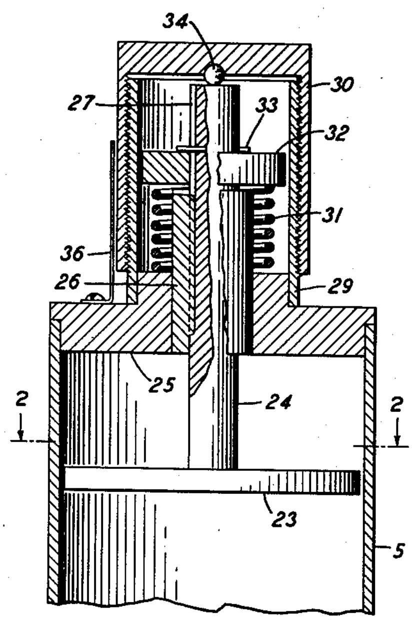
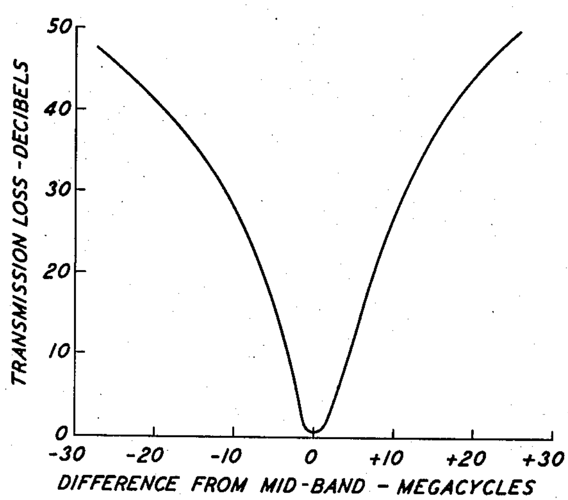


FIG. 4



INVENTORS: J. P. KINZER
R. W. MARSHALL
I. G. WILSON

BY Ralph T. Holcomb
ATTORNEY

United States Patent Office

2,694,186

Patented Nov. 9, 1954

2,694,186

WAVE FILTER

John P. Kinzer, Ridgefield, and Robert W. Marshall, Summit, N. J., and Ira G. Wilson, New York, N. Y., assignors to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application January 4, 1951, Serial No. 204,352

28 Claims. (Cl. 333—73)

This invention relates to frequency-selective electrical devices and more particularly to a wave filter suitable for operation in the microwave region.

A principal object of the invention is to improve the selectivity of a microwave filter.

Another object is to maintain the width of the transmission band of a microwave filter substantially constant while adjusting the mid-band frequency.

Further objects of the invention are to minimize the insertion loss and the distortion within the transmission band of a microwave filter.

In a microwave filter employing a cavity resonator which is resonant for a selected operating mode at the mid-band frequency the response of the resonator to unwanted modes often introduces deep valleys in the transmission loss characteristic outside of the pass band, thus greatly reducing the selectivity of the filter. In accordance with one feature of the present invention this difficulty is largely eliminated by constructing a microwave filter of two or more differently proportioned, electromagnetically coupled, cylindrical cavity resonators. Input coupling means are provided for introducing electromagnetic waves into one of the resonators, and output coupling means for extracting the filtered energy from another of the resonators. The coupling means may, for example, be orifices in the walls of the resonators.

Each of the resonators is resonant at approximately the mid-band frequency for a selected operating mode, which is not necessarily the same for all of the resonators. The resonators differ from one another in diameter, and consequently in length, by an amount sufficient to prevent any two of the resonators from being resonant at the same frequency within or near the transmission band of the filter for any mode other than the selected mode or modes. That is, the frequencies of the undesired responses are staggered so that they will not coincide in any two of the resonators. Consequently, a dip in the loss characteristic due to an extraneous response in one resonator will be effectively filled in by the loss contributed by another of the resonators, thus providing a sustained suppression characteristic for the filter.

The deleterious effects of undesired modes may be further reduced by proper choices of the operating mode or modes, the internal diameters and lengths of the resonators, and the circumferential locations of the input and output coupling means. The transmission loss in the pass band is minimized by making the interior surfaces of the resonators highly conductive and by properly choosing the axial locations, shapes and sizes of the orifices. The distortion in the band is minimized by providing an approximately constant mode shape factor for each resonator and by properly choosing the sizes, shapes and locations of the orifices.

The mid-band frequency of the filter may be made adjustable by providing for each resonator an end plate which is movable longitudinally to change the effective internal length of the cavity. In accordance with another feature of the invention, the width of the band is maintained substantially constant at all settings of the mid-band frequency by proper choices of the axial or longitudinal locations and the sizes and shapes of the coupling orifices.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawings, of which:

Fig. 1 is a perspective view of a microwave filter in accordance with the invention comprising two coupled cylindrical cavity resonators;

Fig. 2 is a horizontal sectional view of the filter, taken at the plane 2—2 in the direction of the arrows as shown in Fig. 3;

Fig. 3 is a fragmentary view of a section taken at a vertical plane through the longitudinal axis of the resonator shown at the left in Fig. 1; and

Fig. 4 is a typical transmission loss-frequency characteristic obtainable with the filter.

The embodiment of the microwave filter in accordance with the invention shown in Figs. 1, 2 and 3 comprises two adjacent, electromagnetically coupled cavity resonators **5** and **6**, in the form of right circular cylinders, each provided with input coupling means and output coupling means. As indicated by the arrow **7**, electromagnetic wave energy from some suitable source, not shown, is introduced into the resonator **5** through the input wave guide **8** and a rectangular input orifice **9** in the side wall of the cylinder.

The output orifice **11** for the resonator **5** and the input orifice **12** for the resonator **6** are circular and of the same diameter. The resonators **5** and **6** are so positioned that their longitudinal axes are parallel and the orifices **11** and **12** are substantially adjoining, thus forming the intercavity coupling. The lower, or fixed ends of the resonators may or may not lie in the same plane. After being filtered, the energy is extracted from the resonator **6** through the output coupling orifice **13** in the side wall of the cylinder and conducted down the output wave guide **14**, as indicated by the arow **15**, to a suitable load, not shown. The source and load each preferably match the characteristic impedance of the associated wave guide.

Each of the cylinders **5** and **6** may, for example, be spun, drawn or turned from some suitable metal such as brass or aluminum. In order to insure that the lower end plates of the cylinders **5** and **6** are substantially perpendicular to the longitudinal axes, leveling means may be provided, if required. In order to obtain a high quality factor, Q, and thus minimize the loss in the pass band, all interior surfaces of the resonators are preferably plated with a metal of high conductivity, such as silver. The cylinders are held together and in proper alignment by means of the bosses **16** and **17**, which may be hard-soldered or brazed to the cylinders and milled to provide a plane surface **18** where they meet. In order to facilitate alignment, pins such as **19** and **20** project from the boss **17** and fit into corresponding holes such as **21** and **22** in the boss **16**. The bosses may be held together by soldering or brazing, or by means of screws or bolts, not shown.

The internal length, and therefore the resonant frequency f, of each of the cylindrical resonators **5** and **6** is made adjustable by means of a movable circular end plate **23** which has a diameter somewhat less than the inner diameter of the cylinder, thus providing a peripheral gap for suppressing extraneous modes having a radial component of the electric field vector. The plate **23** is secured to the end of a piston rod **24** which is free to move axially in the bearing **25** but prevented from rotation by a key **26** carried by the bearing **25** and fitting into a keyway **27** in the rod **24**. Axial adjustment of the rod **24** and the end plate **23** is made by means of a micrometer head comprising an externally threaded inner tube **29** and an internally threaded cylindrical cap **30**. A helical spring **31** acting against a collar **32** and a pin **33** holds the upper end of the rod **24** against a ball bearing **34** seated in the cap **30**. The position of the end plate **23** within the cylinder, and therefore the resonant frequency f of the resonator, is indicated by a circumferential scale **35** on the outside of the cap **30** and a vertical scale **36** secured to the cylinder.

The equivalent electrical circuit of the microwave filter described above comprises two inductively coupled circuits each tuned to resonate at the mid-band frequency f of the filter. The coupling coefficient is chosen to provide a band-pass characteristic with minimum loss and distortion within the transmission band. The design requirements are usually given in terms of the mid-band frequency f, the width of the transmission band, the allowable distortion in the band, and the minimum discrimination between transmitted and suppressed frequencies. These requirements may be translated into the resonant frequency and working quality factor Q of the cavity resonators, and the required coupling coefficient for the filter, by the application of well-known circuit theory such as is presented, for example, in paragraph 5 of section 3 of Terman's Radio Engineer's Handbook, First Edition, published in 1943 by the McGraw-Hill Book Company, Incorporated, New York.

In the embodiment disclosed herein, by way of example only, the requirements called for a substantially constant four-megacycle pass-band with the mid-band frequency f adjustable from 7800 to 8800 megacycles and distortion in the band not exceeding ±0.1 decibel. The mid-band frequency range and the discrimination requirement control the choice of the operating mode to be employed in each of the resonators, and also the diameters and ranges of internal lengths L_1 and L_2 of the resonators. The transverse electric mode designated TE 01n, in accordance with standard notation, is generally to be preferred. The third index number n, which designates the number of half wavelength variations of the field along the axis of the cylinder, may be any integer. In this case, the TE 012 mode was chosen for each of the resonators **5** and **6** because it has a high value of Q and its field configuration simplifies the mechanical design.

The selection of the required internal diameters and lengths L_1 and L_2 of the cylindrical resonators **5** and **6** is preferably based upon a study of appropriate mode charts, such as are described at length in a paper by I. G. Wilson, C. W. Schramm, and J. P. Kinzer entitled "High Q Resonant Cavities for Microwave Testing," in the Bell System Technical Journal, vol. XXV, No. 3, July 1946, pages 408 through 434. Additional pertinent information may be found in a paper by J. P. Kinzer and I. G. Wilson entitled "Some Results on Cylindrical Cavity Resonators," in the Bell System Technical Journal, vol. XXVI, No. 3, July 1947, pages 410 through 445 and in the book "Radar Systems and Components" by members of the Technical Staff of Bell Telephone Laboratories, published in 1949 by the D. Van Nostrand Company, New York. Briefly, a study of the mode chart permits the choice of an operating area in which the required band coverage may be achieved with the least amount of interference from extraneous modes. The selectivity in all cases is related to the geometry of the cavity and the mode of oscillation. The range of ratios of the diameter to the length for each resonator should be such as to provide an approximately constant mode shape factor throughout the tuning range, in order to minimize distortion in the transmission band. The mode shape factor may be expressed as $Q\delta/\lambda$, where Q is the unloaded quality factor for the resonator, δ is the skin depth for the inner surface, and λ is the free-space wavelength.

In accordance with an important feature of the invention the discrimination of the filter is greatly improved by making the inside diameters D_1 and D_2 of the cylindrical resonators **5** and **6** sufficiently different to insure that the resonant frequencies of unwanted modes which occur in or near the transmission band of the filter will be different in the two resonators, even though the resonators have the same resonant frequency f for the operating mode TE 012. This effect can be demonstrated on two appropriate transparent mode charts by placing one over the other and displacing one with respect to the other. However, the permissible difference between the diameters is usually limited by the desire to obtain a maximum tuning range. The choice of the diameters and the choice of the operating area are also influenced by those unwanted modes most troublesome to suppress and the relation of these modes to the operating mode. In the example under consideration, the inside diameter D_1 of the resonator **5** is 2.42 inches and the inside diameter D_2 of the resonator **6** is 2.37 inches, giving a difference of a little more than two per cent.

In accordance with another important feature of the invention, the locations of the orifices **9**, **11**, **12** and **13** are selected to achieve, as nearly as possible, maximum discrimination, minimum loss and distortion throughout the transmission band, and a constant bandwidth for all mid-band frequencies within the tuning range. In each of the resonators **5** and **6** the circumferential angle between the input orifice and the output orifice is so chosen that interference from unwanted modes having certain types of angular periodicity is minimized. In general, these angles are chosen to minimize interference by modes having radial components of the electric field in the neighborhood of the angular coordinate of the center of the output orifice. The choice of angle thus depends upon the particular modes to be suppressed. As shown in Fig. 2, for the filter here considered the angle Φ_1 between the input orifice **9** and the output orifice **11** of the resonator **5**, measured in a clockwise direction, is approximately 90 degrees, and the corresponding angle Φ_2 between the orifices **12** and **13** of the resonator **6** is approximately 135 degrees.

The longitudinal locations of the orifices **9**, **11**, **12** and **13** are dictated principally by the desire to maintain a constant bandwidth at all mid-band settings of the filter. It is found from an analysis of orifice equations such as are presented in Table IV of the above-cited paper in the July 1946 Bell System Technical Journal that the bandwidth will have a minimum variation over the tuning range if, for the input orifice **9** and the output orifice **13**, the distance A from the center of the orifice to the fixed end of the respective cylinder is so chosen that the quantity

$$\frac{\lambda \sin^2\left[\frac{\pi A n}{L}\right]}{\lambda_g L}$$

is kept as nearly constant as possible for all values of the internal length L of the cylinder. The symbol λ represents the free-space wavelength at the mid-band operating frequency f, λ_g is the wavelength at the same frequency in the wave guide associated with the orifice, and n is the index defined above. In the filter under consideration, n is two. The longitudinal spacings of the orifices **9** and **13** from the respective fixed ends of the resonators **5** and **6** determined by the foregoing considerations are not necessarily the same in both of the resonators.

Similar considerations show that, for maximum constancy of the bandwidth, the distance B from the center of the output orifice **11** of the resonator **5** to the fixed end thereof and the distance C from the center of the input orifice **12** of the resonator **6** to its fixed end are chosen to make the quantity

$$\frac{\lambda \sin\left[\frac{\pi B n}{L_1}\right] \sin\left[\frac{\pi C n}{L_2}\right]}{L_1 L_2}$$

as nearly constant as possible over the tuning range, where L_1 and L_2 are the internal lengths of the resonators **5** and **6**, respectively. Since the optimum values of the distances B and C chosen in this way may not be the same, it follows that the lower ends of the cylinders **5** and **6** may not be in the same plane.

Each of the distances A, B and C will be approximately equal to $L/2n$. In the filter under consideration the variation in the bandwidth was held to limits of less than 11 per cent by making the distance A for the input orifice **9** equal to 1.275 inches, the corresponding distance for the output orifice **13** equal to 1.340 inches, and the distances B and C each equal to 1.245 inches. A typical transmission loss-frequency characteristic for one setting of the filter is shown in Fig. 4, where the loss in decibels is plotted against the difference of the frequency in megacycles from the mid-band frequency f. The filter has a low and substantially constant loss within the transmission band of approximately four megacycles and a steeply rising suppression characteristic on either side of the band, with no discernible dips caused by interfering modes over the range from 30 megacycles below to 30 megacycles above f.

The required diameter of the orifices **11** and **12** may be calculated to a first approximation from formulas found in the references cited above. However, these formulas assume that the orifice is located in a very thin wall. Generally the walls of practical resonators, such as **5** and **6**, are thick enough to require that the diameter of the orifice be corrected to allow for the thickness of the wall. The correction to be applied may be found by experiment.

What is claimed is:

1. A microwave filter comprising two cylindrical cavity resonators each resonant for a selected TE 01n operating mode at approximately the mid-band frequency of the filter, means for adjusting the effective electrical lengths

of said resonators to adjust said frequency over a range, and intercavity coupling means having a coupling coefficient such that a desired band-pass characteristic is imparted to the filter, said resonators having different inside diameters so chosen that, for all frequency adjustments within said range, all resonances for non-selected modes falling within or near the transmission band of the filter occur at respectively different frequencies in each of said resonators, thereby improving the discrimination of the filter.

2. A filter in accordance with claim 1 in which the operating mode of each of said resonators is the TE 012 mode.

3. A filter in accordance with claim 1 in which for each of said resonators the range of ratios of said diameter to said length is chosen to provide an approximately constant mode shape factor throughout the adjustable range.

4. A microwave filter comprising two cylindrical cavity resonators each resonant for a selected TE 01n operating mode at the mid-band frequency f of the filter, an input coupling device, an output coupling device, and an adjustable end plate associated with each of said resonators, means including an input wave guide for introducing electromagnetic wave energy into one of said resonators through its input coupling device, means for connecting said output coupling device of said one resonator and said input coupling device of the other of said resonators, and means including an output wave guide for extracting filtered energy from said other resonator through its output coupling device, the center of said input coupling device in said one resonator and the center of said output coupling device in said other resonator each being spaced from the end opposite said adjustable end plate a distance A so chosen that the quantity

$$\frac{\lambda \sin^2\left[\frac{\pi A n}{L}\right]}{\lambda_g L}$$

is kept as nearly constant as possible for all positions of said end plate, where λ is the free-space wavelength at the frequency f, λ_g is the wavelength at the frequency f in the wave guide associated with the coupling device, L is the internal length of the resonator, and n is the number of half wavelength variations of the field along the longitudinal axis of the resonator for the operating mode of the resonator.

5. A filter in accordance with claim 4 in which said resonators differ from each other in inside diameter to prevent both of said resonators from being resonant at the same frequency within or near the transmission band of the filter for any mode other than the selected operating mode or modes of said resonators.

6. A filter in accordance with claim 4 in which the center of said output coupling device in said one resonator is spaced a distance B from the end of the resonator opposite said adjustable end plate and the center of said input coupling device in said other resonator is spaced a distance C from the end of the resonator opposite said adjustable end plate, said distances being chosen to make the quantity

$$\frac{\lambda \sin\left[\frac{\pi B n}{L_1}\right] \sin\left[\frac{\pi C n}{L_2}\right]}{L_1 L_2}$$

as nearly constant as possible for all positions of said end plates, where L_1 and L_2 are the internal length, respectively, of said resonators.

7. A filter in accordance with claim 6 in which said resonators differ from each other in inside diameter to prevent both of said resonators from being resonant at the same freqeuncy within or near the transmission band of the filter for any other than the selected operating mode or modes of said resonators.

8. A filter in accordance with claim 4 in which in each of said resonators the circumferential angle between said input coupling device and said output coupling device is chosen to minimize interference by modes having radial components of the electric field in the neighborhood of the angular coordinate of the center of said output coupling device.

9. A filter in accordance with claim 8 in which said resonators differ from each other in inside diameter to prevent both of said resonators from being resonant at the same frequency within or near the transmission band of the filter for any other than the selected operating mode or modes of said resonators.

10. A microwave filter comprising two cylindrical cavity resonators, each of said resonators being resonant for a selected TE 01n operating mode at approximately the mid-band frequency of the filter, including an adjustable end plate for adjusting said frequency over a range, and having an input orifice and an output orifice, and means for connecting said output orifice of one of said resonators and said input orifice of the other of said resonators to constitute an intercavity coupling having a coupling coefficient such that a desired band-pass characteristic is imparted to the filter, said resonators having different inside diameters so chosen that, for all frequency adjustments within said range, all resonances for non-selected modes falling within or near the transmission band of the filter occur at respectively different frequencies in each of said resonators, thereby improving the discrimination of the filter.

11. A filter in accordance with claim 10 in which the operating mode of each of said resonators is the TE 012 mode.

12. A filter in accordance with claim 10 which includes means for indicating the internal lengths of said resonators.

13. A filter in accordance with claim 10 in which for each of said resonators the circumferential angle between said input orifice and said output orifice is chosen for maximum discrimination between transmitted and suppressed frequencies.

14. A filter in accordance with claim 10 in which the size, shape, and axial location of each of said orifices are chosen for minimum loss within the transmission band of the filter.

15. A filter in accordance with claim 10 in which the size, shape, and location of each of said orifices are chosen to minimize the distortion in the transmission band of the filter.

16. A filter in accordance with claim 10 in which for each of said resonators the range of ratios of said diameter to the internal length of the resonator is chosen to provide an approximately constant mode shape factor for all positions of said end plate.

17. A filter in accordance with claim 10 in which for each of said resonators the shapes, sizes and axial locations of said orifices are chosen to provide maximum constancy of bandwidth for all position of said end plate.

18. A band-pass wave filter adapted for operation in the microwave region comprising two cylindrical cavity resonators, input coupling means associated with one of said resonators, output coupling means associated with the other of said resonators, means for electromagnetically coupling said resonators, and a movable end plate associated with each of said resonators, both of said resonators being resonant at substantially the same frequency for a selected TE 01n operating mode but differing from each other in inside diameter, the diameters of said resonators and the circumferential locations of said coupling means being chosen to minimize the deleterious effects of undesired modes, and the axial locations and coupling coefficients of said coupling means being chosen to provide the desired width of transmission band and to maintain said width as nearly constant as possible for all positions of said end plates.

19. A filter in accordance with claim 18 in which the operating mode of each of said resonators is the TE 012 mode.

20. A filter in accordance with claim 1 in which the inside diameters of said resonators differ by at least one per cent.

21. A filter in accordance with claim 1 in which the inside diameters of said resonators differ by at least two per cent.

22. A filter in accordance with claim 1 in which the inside diameters of said resonators differ by approximately two per cent.

23. A filter in accordance with claim 1 which includes means for indicating the internal lengths of said resonators.

24. A filter in accordance with claim 4 which includes means for indicating the internal lengths of said resonators.

25. A filter in accordance with claim 4 in which the inside diameters of said resonators differ by approximately two per cent.

26. A filter in accordance with claim 10 in which the

inside diameters of said resonators differ by approximately two per cent.

27. A filter in accordance with claim 18 which includes means for indicating the internal lengths of said resonators.

28. A filter in accordance with claim 18 in which the inside diameters of said resonators differ by approximately two per cent.

References Cited in the file of this patent

UNITED STATES PATENTS

Number	Name	Date
2,496,772	Bradley	Feb. 7, 1950
2,513,761	Tyson	July 4, 1950
2,522,861	Cork	Sept. 19, 1950
2,540,839	Southworth	Feb. 6, 1951
2,560,353	Kerwien	July 10, 1951
2,619,539	Fano	Nov. 25, 1952

OTHER REFERENCES

Publication I, "High Q Resonant Cavities for Microwave Testing" by Wilson, Schramm, and Kinzer, published July 1946 in Bell System Technical Journal, vol. XXV, No. 3, pp. 408-434. (Copy in Div. 16.)