Dec. 8, 1959 N. F. ARTUSO 2,916,712

MICROWAVE DIPLEXER

Filed July 9, 1954 3 Sheets-Sheet 1

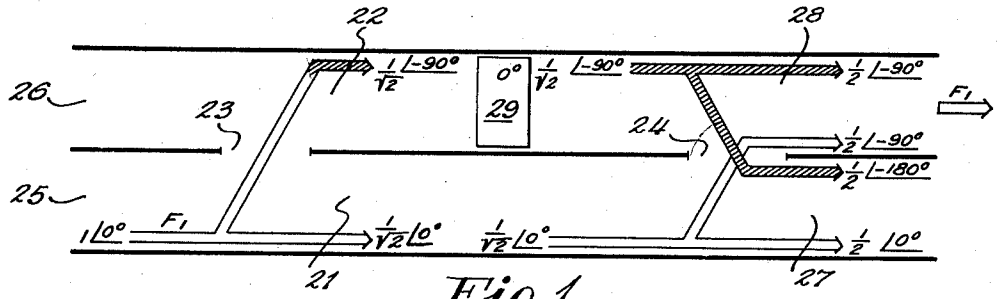

Fig. 1.

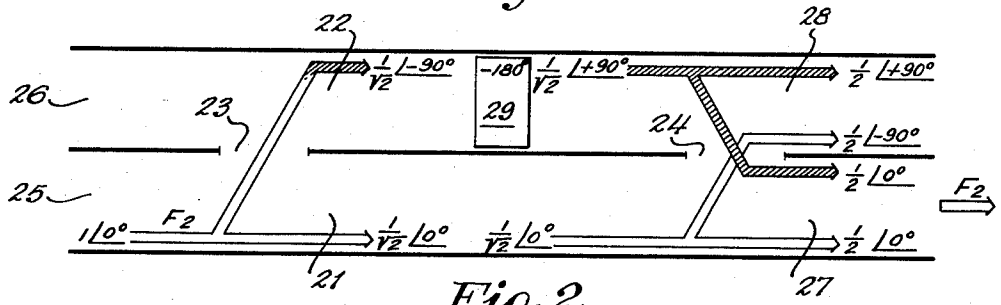

Fig. 2.

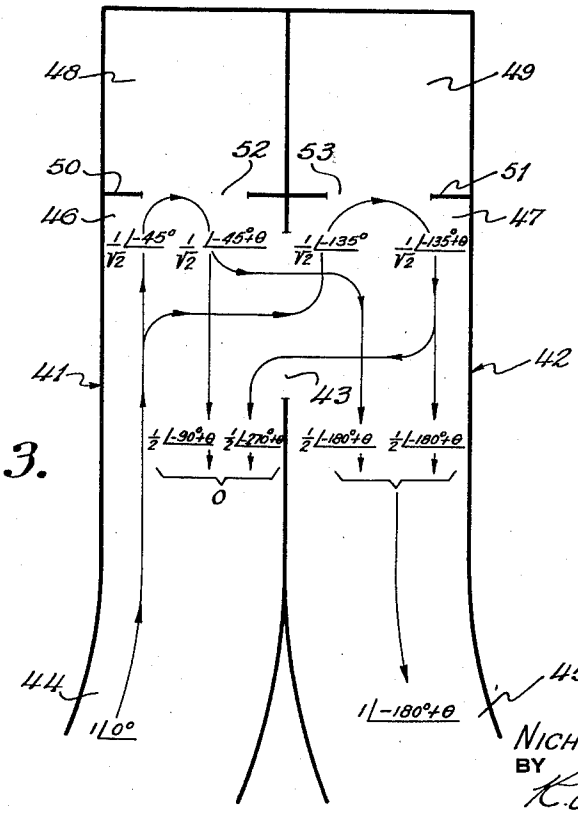

Fig. 3.

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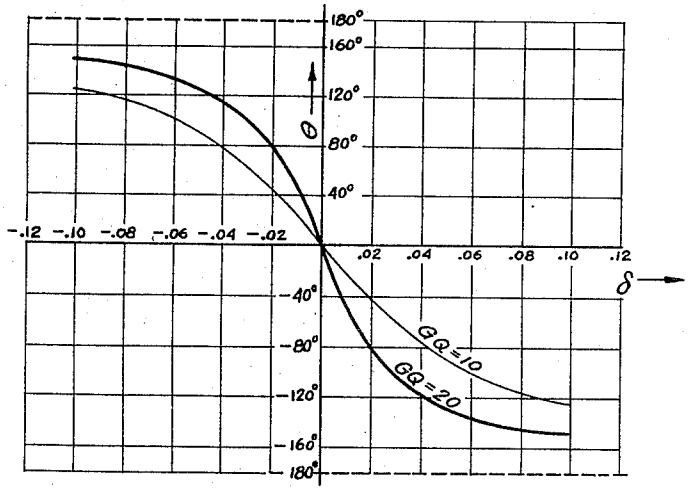

Fig. 4.

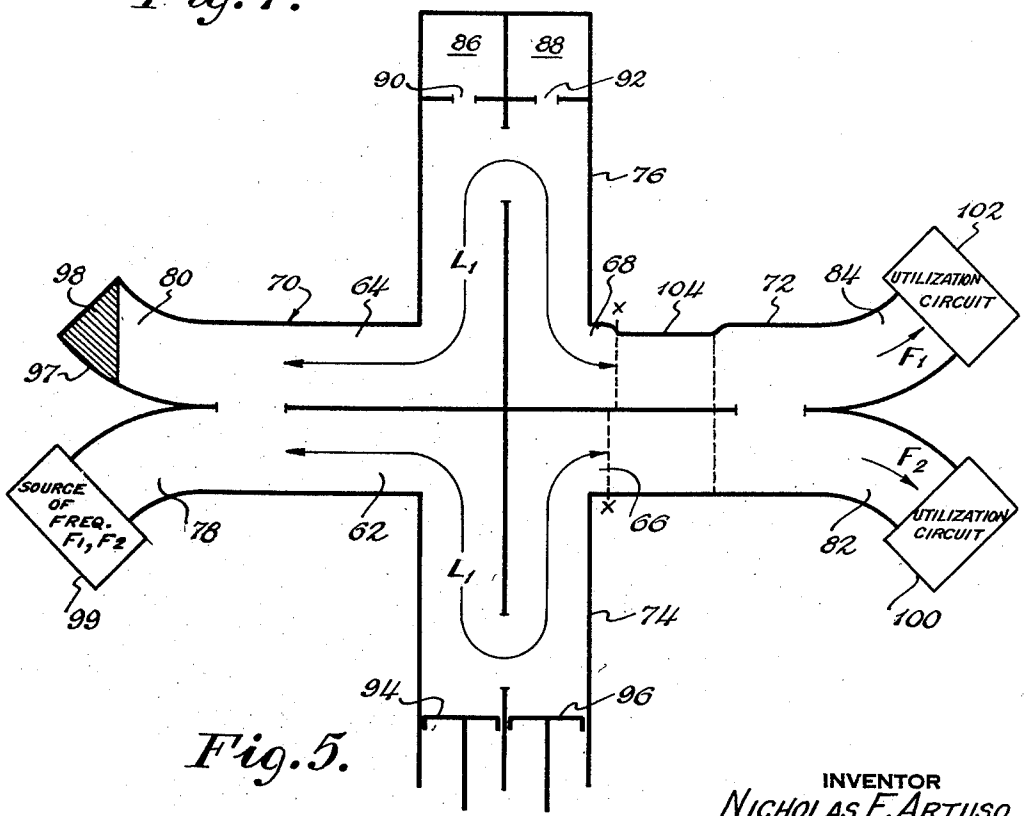

Fig. 5.

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MICROWAVE DIPLEXER

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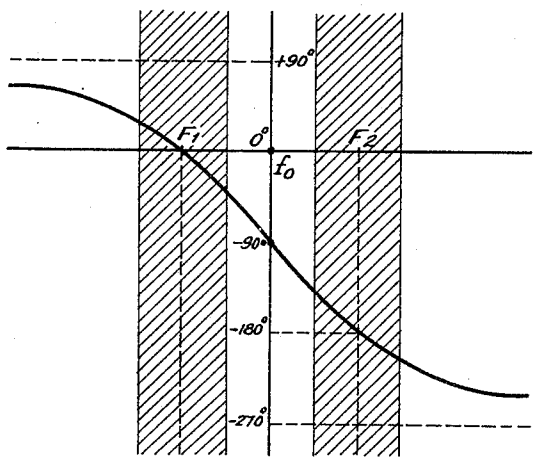

Fig. 6.

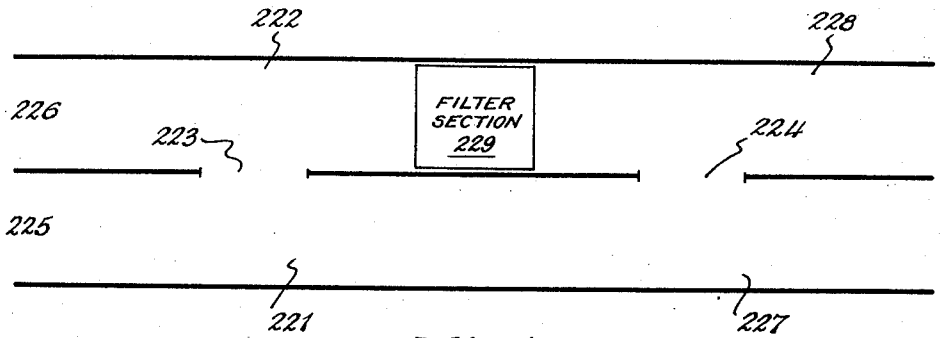

Fig. 7.

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2,916,712

MICROWAVE DIPLEXER

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Application July 9, 1954, Serial No. 442,257

6 Claims. (Cl. 333—73)

This invention relates to diplexer systems and more particularly is concerned with apparatus for coupling two electromagnetic microwave signals of different frequencies to a single electromagnetic wave transmission line or for separating two electromagnetic microwave signals of different frequencies into different electromagnetic wave transmission lines.

A diplexer system is disclosed in U.S. patent application Serial No. 360,327 of K. Tomiyasu. Such microwave diplexer comprises in effect a pair of four-terminal hybrid junctions having a conjugate pair of arms of each interconnected by two sections of wave guide transmission line of different lengths. One of the line sections is of a fixed length and the other line section is of a substantially different and variable length. Diplexing is achieved when the two frequencies and the lengths of the two transmission lines satisfy two conditions of operation. First, the length of one of the transmission line sections must be an odd number of half guide wavelengths longer at one frequency than at the other frequency. Second, the length of the other transmission line section must be an even number of half guide wavelengths longer at one frequency than at the other frequency. Thus, the allowable change in frequency about a particular diplexing frequency (the bandwidth) is a function of the path length between the two hybrid junctions. The greater the dierence in path lengths between the two hybrid couplers, the greater is the phase sensitivity between the two transmission lines as a function of frequency and the smaller is the operable bandwidth.

Another characteristic of the Tomiyasu diplexer is the method of adjusting the system to achieve proper diplexing action for a specified pair of frequencies. This adjustment is achieved by varying the length of the variable length transmission line until the specified two conditions of operation occur.

It is therefore a principal object of this invention to provide a diplexer apparatus which improves upon the features of the Tomiyasu diplexer described above.

Another object of this invention is to provide a microwave diplexer whose diplexing action is independent of the length differential of the microwave transmission lines utilized.

Another object of this invention is to provide a diplexer system which is capable of diplexing different pairs of operating frequencies with little adjustment effort.

Another object of this invention is to provide a diplexer system which is simple and inexpensive in construction.

Another object of this invention is the provision for a microwave diplexer capable of operating at the high peak powers encountered in a radar transmission system.

Another object of the invention is to provide a diplexer apparatus which is operable over a relatively wide band of frequencies.

Another object of this invention is to provide a diplexer whose bandwidth is determined solely by the

bandwidth of a cavity resonator having a relatively low loaded Q.

Another object of this invention is to provide a microwave diplexer whose bandwidth is determined solely by the bandwidth of a microwave filter device.

Another object of this invention is to provide a microwave diplexer which may be tuned by the adjustment of a cavity resonator tuner.

Another object of this invention is to provide a non-reflective frequency-sensitive phase shifting means for use in a diplexer system.

In accordance with the present invention there is provided a system for diplexing two frequencies which comprises a pair of four-terminal hybrid junctions, one conjugate pair of each junction being connected together by means of a pair of electromagnetic wave transmission lines whose difference in electrical length remains constant. Inserted in one of these transmission lines is means for causing the phase of one of the signals to be shifted by an amount 180° different from that of the other frequency. This phase shifting means is adjustable in order that different pairs of frequencies may be diplexed by the system.

Other objects and advantages of the present invention will become apparent from the specification taken in connection with the accompanying drawings, wherein:

Figs. 1 and 2 are schematic views useful in explaining the operation of the diplexer of the present invention;

Fig. 3 is a schematic view of the non-reflective frequency-sensitive phase shift element used for diplexing action;

Fig. 4 is a graph showing the variation in reflection coefficient phase angle as a function of frequency, for a cavity resonator;

Fig. 5 is a schematic view useful in explaining the preferred form of the invention;

Fig. 6 is a graph showing the combined phase shifts of the cavity resonator and 90° phase shifting region of the structure of Fig. 5; and

Fig. 7 is a schematic view of a modified form of the invention in which the shunt cavity resonator elements are replaced by a tandem filter-type element.

Referring to the schematic drawing of Fig. 1, the numerals 21 and 22 indicate a pair of electromagnetic wave transmission lines such as coaxial transmission lines or wave guide transmission lines. The two transmission line are coupled together by a pair of spaced hybrid junctions. These hybrid junctions may be either the magic tee type or the hybrid directional coupler type.

A hybrid junction is an essentially lossless device which at high frequencies may take the form of a metal enclosure at the junction of four transmission lines. The hybrid junction guides waves from one to another of the four lines in a particular way. A fundamental property of the junction is that when its four arms are completely matched, the entries may be paired in such a way that no power flow exists between entries of a pair. Such a pair is called a conjugate pair of arms. Thus, each hybrid junction contains two conjugate pairs of arms. A second significant property is that when power enters one of the arms of either conjugate pair, it will divide equally and flow out the two arms of the other conjugate pair. The relative phase angle of these two equal outputs will depend on the type of hybrid junction used. Several types of hybrid junctions are well known in the art; in particular, the magic tee and the hybrid directional coupler. In the magic tee, the relative phase angles of the two equal output powers are separated by either 0° or 180°, depending on the arm into which the power is injected. In the instance of the hybrid directional coupler, regardless of the arm into which the power is in-

jected, the relative phase between the two equal output powers will always be 90°.

For illustrative purposes, hybrid directional couplers **23** and **24** are indicated in Fig. 1. In the hybrid directional coupler energy entering any one of the four arms will leave equally the two opposite output arms. While the energy leaving the two output arms is equal, the phase angle of that portion of the energy which passes through the coupling element, known as the coupled wave, will lag by 90° the phase angle of that energy which does not pass through the coupling element, known as the direct wave.

In operation, an electromagnetic signal of frequency F_1 with a relative electric vector amplitude of unity and a phase angle of 0° is shown entering an arm **25** of hybrid directional coupler **23**. The energy divides equally at the coupler **23**, half of it (termed the direct wave) passing directly into transmission line **21**, and the other half (termed the coupled wave) passing through the coupling element of the hybrid directional coupler into transmission line **22**. The amplitude of the direct wave will have a value of

$$\frac{1}{\sqrt{2}}$$

at a relative phase angle of 0°, while the amplitude of the coupled wave will have an amplitude of

$$\frac{1}{\sqrt{2}}$$

at an angle of 90° lagging. It is to be noted that an equal additional phase delay of 45° is introduced into both waves in passing the hybrid junction. This will not be considered here since it plays no part in the operation of the device. A frequency sensitive phase shift element **29** inserted in transmission line **22** is designed to produce no phase delay for signals of frequency F_1. Since the transmission lines **21** and **22** are equal in length between the couplers **23** and **24** they will produce the same electrical phase delay of both the direct and coupled waves, and consequently the direct and coupled waves will reach the input end of the hybrid directional coupler **24** with their relative phase relationship unchanged.

The energy entering the coupler **24** from transmission line **21** will divide equally, half of it passing into the arm **27** and half passing into the arm **28**. The portion passing into arm **27** will have an amplitude of one-half and a relative phase angle of 0°. The portion entering arm **28** will have an amplitude one-half and a relative phase angle of −90°. The signal entering coupler **24** from transmission line **22** will also divide equally, half entering the arm **27** and half entering the arm **28**. The portion entering the arm **28** will be unchanged in phase, remaining at a relative angle of −90° and having an amplitude of one-half. The portion entering arm **27** will be further retarded in phase by 90°, thereby having a phase angle of −180° and an amplitude of one-half. The two signals entering arm **27** are equal in amplitude but opposite in phase and thereby cancel, resulting in no energy of frequency F_1 leaving arm **27**. The two signals entering arm **28** are alike in phase and add, resulting in a signal of frequency F_1 leaving arm **28**. Thus, all of the energy which entered the arm **25** at frequency F_1 will leave the diplexer at arm **28** and none will leave arm **27**.

Consider now Fig. 2 in which the energy entering arm **25** is at a different frequency F_2. For energy at this frequency, the phase shift element **29** will produce a phase lag of 180° as energy passes through or by the element. The frequency F_2 entering arm **25** has unity amplitude and a relative phase angle of 0°. This signal divides equally at the hybrid directional coupler **23**, half of it passing into transmission line **21** and half into transmission line **22**. The portion passing into line **21** will have an amplitude of

$$\frac{1}{\sqrt{2}}$$

at a relative phase angle of 0°. The portion passing into line **22** will have an amplitude

$$\frac{1}{\sqrt{2}}$$

at a relative phase angle of −90°. Since the two lines **21** and **22** are equal in length between the directional couplers **23** and **24**, the only difference in the relative phase of the two waves propagating along these arms will be caused by the phase delay inserted by phase shift element **29**. Since the wave propagating in line **22** entered that line lagging the wave propagating in line **21** by 90°, it will further lag that wave by 180°, or a total of 270°, when it reaches the directional coupler **24**. For convenience this wave in line **22** is shown arriving at coupler **24** at a phase angle +90° rather than a phase angle of −270°. The energy from line **21** entering coupler **24** will divide equally and pass into arms **27** and **28**. That portion entering arm **27** will have an amplitude of one-half and a relative phase angle of 0°. That portion entering arm **28** will have an amplitude of one-half and a relative phase angle of −90°. The energy entering the coupler **24** from line **22** will divide equally, half passing out arm **27** and half out arm **28**. The portion leaving arm **28** has an amplitude of one-half and a relative phase angle of 90°. The portion leaving arm **27** is further delayed in phase by 90° and leaves at a relative phase angle of 0° and an amplitude of one-half. The two signals leaving arm **27** are equal in amplitude and alike in phase so that a signal of amplitude unity at the frequency F_2 leaves arm **27**. The two signals leaving arm **28** are equal in amplitude but opposite in phase and thereby cancel, so that no energy leaves arm **28**. Thus all of the signal which entered arm **25** at frequency F_2 will leave the diplexer at arm **27** and none will leave arm **28**.

If the operation of Figs. 1 and 2 are combined, such that signals of frequency F_1 and F_2 enter the diplexer at arm **25**, it is seen that all of the energy of frequency F_1 will leave arm **28** and all of the signal of frequency F_2 will leave arm **27**, the two signals thereby being separated.

A preferred form of the frequency sensitive phase shift element is shown schematically in Fig. 3. Two electromagnetic wave transmission lines **41** and **42** are coupled together by means of a hybrid junction such as the directional coupler **43**. Microwave energy enters the device through arm **44** and leaves through arm **45**. The energy leaving arm **45** differs in phase from that entering by an amount which depends on the frequency of transmission. Arms **44** and **45** constitute a conjugate pair of arms. Connected to the second conjugate pair of arms **46** and **47** are a pair of resonant cavities **48** and **49**. The resonant cavities **48** and **49** are separated from the arms **46** and **47** by the respective apertured walls **50** and **51** which contain the respective apertures **52** and **53**.

If a wave external to the cavity is incident on apertured wall **50** or **51**, it will be reflected with unchanged magnitude but with a phase angle which is a function of frequency. A curve of the reflection coefficient angle for such a wave as a function of the fractional deviation δ from the resonant frequency of the cavity is shown in Fig. 4. The curves plotted are for different values of cavity GQ which represent the product of the normalized shunt conductance G times the Q of the cavity.

To analyze this frequency sensitive phase shift element assume a wave of amplitude unity at relative phase angle 0° entering arm **44**. For this analysis, the 45° phase lag of the direct wave due to the coupler is included in the

assigned phase angles. This wave will divide equally at hybrid coupler 43 half entering arm 46 and half entering arm 47. The portion entering arm 46 has an amplitude

$$\frac{1}{\sqrt{2}}$$

at a phase angle 45°. The portion entering arm 47 has an amplitude

$$\frac{1}{\sqrt{2}}$$

at a phase angle −135° due to the additional 90° phase delay caused by passing through the coupling element. The waves in arms 46 and 47 directed toward the respective resonant cavities 48 and 49 are reflected therefrom and return along their prior paths unchanged in magnitude, but further retarded in phase by the phase angle θ of the reflection coefficient, as indicated in Fig. 4. The reflected wave in arm 46 divides at hybrid coupler 43 half entering arm 44 and half entering arm 45. The portion entering arm 44 has an amplitude of one-half at a phase angle $-90°+\theta$. The portion entering arm 45 has an amplitude one-half at a phase angle $-180°+\theta$. The reflected wave in arm 47 divides equally at hybrid coupler 43 half entering arm 44 and half entering arm 45. The portion entering arm 44 has an amplitude one-half at a phase angle $-270°+\theta$. The portion entering arm 45 has an amplitude one-half at a phase angle $-180°+\theta$. The two wave portions which tend to return in arm 44 are equal in amplitude but opposite in phase and consequently cancel, no energy propagating backward along arm 44. The two wave portions entering arm 45 are equal in amplitude and alike in phase, thereby adding and causing a wave of amplitude unity at a relative phase angle $-180°+\theta$ to leave arm 45. The unit thus described transmits all the energy from the input arm to the output arm with no energy being reflected, the energy leaving the output arm bearing a phase relative to that entering the input arm which is dependent on the frequency of the energy. This, therefore, is a non-reflective frequency sensitive phase shifter.

Fig. 5 illustrates a schematic diagram of an embodiment of this invention. The numerals 62, 64, 66 and 68 indicate sections of hollow rectangular wave guide. The numerals 70, 72, 74 and 76 indicate hybrid directional couplers. A suitable hybrid directional coupler is described in the Proceedings of the I.R.E., February 1952, page 180. The wave guide sections 62 and 64 are coupled together near one of their extremities by the hybrid directional coupler 70. In a like manner the wave guide sections 64 and 68, 68 and 66, and 62 and 66 are coupled together by the respective hybrid directional couplers 76, 72 and 74. The wave guide sections 62 and 64 are connected to the respective input arms 78 and 80. The wave guide sections 66 and 68 are connected to the respective output arms 82 and 84. Connected to one end of the hybrid directional coupler 76 are resonant cavities 86 and 88. Energy is coupled to resonant cavities 86 and 88 by means of the respective coupling apertures 90 and 92. The wave guide sections 64 and 68, the hybrid coupler 76, and the cavities 86 and 88 comprise a frequency sensitive phase shift element as heretofore described. Connected to one end of the hybrid directional coupler 74 are wave guide short circuits 94 and 96.

A non-reflecting energy absorbing termination is indicated generally at 97 in the input arm 80. Energy absorbing material such as polyiron or a mixture of graphite and cement, indicated at 98, is inserted in the input arm 80 to provide such non-reflective termination. A source of energy 99 of two different frequencies F_1 and F_2 is connected to the input arm 78. A utilization circuit 100 for a signal of frequnecy F_2 is connected to the output arm 82 and a utilization circuit 102 for a signal of frequency F_1 is connected to the output arm 84. Such utilization circuit may, for example, be a receiver.

The wave guide short circuits 94 and 96 must be so positioned that the total length of the wave guide sections 64 and 68 between the hybrid directional couplers 70 and 72 must be substantially equal to the total length of the wave guide sections 62 and 66 between the same hybrid directional couplers. With the wave guide shorts 94 and 96 so adjusted the phase difference of the two waves arriving at coupler 72 from wave guides 66 and 68 will be independent of the absolute lengths of the wave guide sections between the couplers 70 and 72 for a substantial range of frequencies. This phase difference is not dependent on any critical guide wavelengths which vary with frequency, but is due solely to the 90° difference introduced at coupler 70 and any artificially introduced phase shifts which cause the phase delay along one path to be different from that along the other path. Recalling from the analysis of Figs. 1 and 2, that diplexing action will be achieved if the phase shift element 29 produces a phase delay which is 180° different at one of the frequencies than at the other, it has been found that for greatest bandwidth operation if resonant cavities, which have the characteristics shown in the curve of Fig. 4, are utilized for the phase shift element, the diplexing frequency is preferably selected at those points on the curve which indicate reflection coefficient angles of +90° and −90°, although any two points which differ by 180 degrees may be selected.

Thus for the lower frequency F_1, the wave entering wave guide 64 lags that of wave guide 62 by 90° and will arrive at the dotted section XX of wave guide 68 lagging the wave in wave guide 66 arriving at the same section, by an additional 270°. The phase difference between these two waves of wave guides 66 and 68, for the lower frequency F_1, on arriving at dotted section XX is 0°. By a similar analysis the higher frequency F_2 arriving at the dotted section XX in wave guide section 68 lags that in wave guide 66 by 180°. If the signals at these two frequencies were permitted to reach coupler 72 with their relative phase angles unchanged, no diplexing action would occur, but instead equal energy would pass out both output arms 82 and 84 for both frequencies. To correct for this difficulty, means must be included in one of the wave guide sections 62, 64, 66 or 68 to cause the electrical length of said section to differ by 90° from the electrical length of the other sections. Such a scheme is shown at region 104. In this region, the wave guide section 68 is changed in form so as to cause its electrical length to differ from that of wave guide 66 by 90° for the entire band of frequencies at which the diplexer operates. The particular means utilized is to decrease the width of the wave guide 68. Other means for obtaining this 90° phase shift may be used, such as dielectric loading of a wave guide section or ridge loading of a wave guide section.

This added phase shift means in wave guide section 68 introduces an added 90° phase difference between the respective waves propagating in wave guides 68 and 66. The energy of the lower frequency F_1 being diplexed reaching directional coupler 72 from wave guide section 68 lags in phase by 90° that reaching the coupler from arm 66 for the embodiment shown. This lower frequency F_1 will then leave the diplexer at output arm 84. The signal at the upper frequency F_2 will now arrive at coupler 72 from the wave guide section 68 lagging by 270° the energy of wave guide section 66. Therefore, the energy at this upper frequency F_2 will all leave the diplexer at output arm 82. Fig. 6 shows a curve of the combined phase delays of region 104 and that of resonant cavities 86 and 88. It is noted that at the diplexing frequencies this phase difference is the required 0° and 180°.

To determine an appropriate bandwidth for a diplexer, a standard must be established. A useful standard is the frequency range over which the phase difference of the signals arriving at the second hybrid coupler 72 does not deviate by more than 30° from the required phase difference for diplexing. Within this 60° frequency

band, centered about the diplexing frequency, the insertion loss for the transmitted signal will always be below 0.5 db, allowing for 0.2 db losses in the wave guide walls and spurious reflections.

This standard is indicated by the boundaries of the shaded areas of Fig. 6. An analysis of the system shows that the bandwidth achieved by this method is two-thirds the frequency difference between the resonant frequency f_0 of the cavity and the extreme ends of the diplexing range.

In designing the resonant cavities for this system, the resonant frequency f_0 is selected midway between the desired diplexed frequencies. To determine the required Q of the cavity it is then necessary merely to determine that cavity whose Q will yield reflection coefficient angles of $+90°$ and $-90°$ at the respective frequencies to be diplexed. Solution of the equation

$$\theta \approx \arctan\left[\frac{-4GQ\delta}{1-(2GQ\delta)^2}\right]$$

for the product GQ, where θ equals 90°, will supply the necessary information. The normalized shunt conductance G is determined from the allowable losses.

To enable this device to diplex different frequencies, the resonant cavities may be made tunable. The use of cavity tuning means such as adjustable shorts or plungers will allow changing the cavity resonant frequencies and cavity Q, and thereby permit rapid changing of the diplexed frequencies.

By considering the well-known principles of reciprocity, it may be seen that if a source of energy of frequency F_1 is connected to arm **84** and a source of energy of frequency F_2 is connected to arm **82**, the two signals will be combined by this device so as to leave the diplexer at arm **78**. Thus, this invention may be utilized for combining into one electromagnetic wave transmission line signals from two independent transmission lines.

An alternative embodiment of this invention is disclosed in Fig. 7. In this form of the invention the frequency sensitive phase shift element **229** is a wave guide filter section. The frequency sensitive phase shift element **229** is coupled to wave guide section **222**, which in turn is coupled to wave guide section **221** by the separated hybrid directional couplers **223** and **224**. Known in the art are many forms of wave guide filter sections which will produce a varying phase shift as a function of frequency in the pass band so as to satisfy the requisites of this device. In addition, such filters are known which can have a relative impedance equal to the characteristic impedance of the wave guide over the band of frequencies. An example of such a filter is an m-derived band pass filter.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings, shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. A non-reflective frequency sensitive phase shifter comprising a hybrid directional coupler, two electromagnetic wave transmission line sections having first and second ends coupled together intermediate their ends by said coupler, and two similar cavity resonators coupled to the first ends of said line sections.

2. A diplexer transmission system comprising four hybrid junctions, each junction having two conjugate pairs of arms, four hollow rectangular waveguide sections, each section coupling the first arm of the first conjugate pair of arms of one of said junctions to the second arm of the first conjugate pair of arms of another of said junctions, a pair of resonant cavities coupled to the second conjugate pair of arms of one of the hybrid junctions, and a 90° phase shifting means in one of said hollow rectangular waveguide sections.

3. A diplexer transmission system comprising three hollow rectangular waveguide sections, a first hybrid junction coupling the first and second of said waveguide sections, a second hybrid junction coupling the first and third of said waveguide sections, a third hybrid junction, said second and third waveguide sections being coupled to one conjugate pair of arms of said third hybrid junction, two cavity resonators, one coupled to each of the arms of the other conjugate pair of arms of said third hybrid junction, and a 90° phase shifting means in one of said hollow rectangular wave guide sections.

4. A diplexer transmisison system comprising four hybrid junctions, each junction having two conjugate pairs of arms, four hollow rectangular waveguide sections, each section coupling the first arm of the first conjugate pair of arms of one of said junctions to the second arm of the first conjugate pair of arms of another of said junctions, a pair of resonant cavities coupled to the second conjugate pair of arms of one of the junctions, shorting means connected to the second conjugate pair of arms of another of said junctions, and a 90° phase shifting means in one of said hollow rectangular waveguide sections.

5. A diplexer transmisison system comprising two hybrid junctions, first and second hollow rectangular waveguide sections coupled together at each of two separated positions by means of said hybrid junctions, a frequency sensitive phase shifting means positioned in one of the wave guide sections intermediate said junctions, said means including third and fourth hollow rectangular waveguide sections connected by a third hybrid junction, each of said waveguide sections having first and second ends, cavity resonator means connected to the first end of each of said third and fourth waveguide sections, the second ends of said third and fourth waveguide sections being connected into the first waveguide section, and a phase shifting means in one of said hollow rectangular waveguide sections.

6. A non-reflective frequency sensitive phase shifter comprising a hybrid directional coupler having two conjugate pairs of arms and a pair of similar cavity resonators connected to one conjugate pair of arms.

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