

- [54] MINIATURIZED FERRIMAGNETIC CIRCULATOR FOR MICROWAVES
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- [73] Assignee: Trak Microwave Corporation, Tampa, Fla.
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- [52] U.S. Cl. 333/1.1, 333/84 M
- [51] Int. Cl. H01p 1/32
- [58] Field of Search 333/1.1

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[57]

ABSTRACT

A compact strip line type microwave circulator having an internal line impedance matching means is formed by a central conductor plate with spirally slotted conductor arms connected to suitable input and output ports, wherein the length of the slots bears a direct relation to a fractional wavelength of the microwave energy to be circulated and to the impedance of the input and output lines to be matched. The spiral cut central conductor plate is sandwiched between a pair of ferrite circulator elements, the opposite faces of the ferrite elements are bounded by parallel conductive ground planes, a pair of fixed magnets are positioned in intimate contact with the opposite ground plane conductors, and the entire assembly is enclosed within a steel housing containing a spring steel wafer to maintain pressure contact between abutting parallel surfaces of all elements in the sandwiched structure. In one embodiment a high loss ferrite attenuator is included within the sandwich assembly, coupled to a terminator port arm, and biased into resonance by the circulator fixed magnets to provide fail-safe internal termination — all within a unitary structure of only approximately $\frac{3}{4} \times \frac{3}{4} \times \frac{1}{2}$ inch external dimensions in the 1.5 GHz to 3.0 GHz range. In another embodiment a circulator was developed at 975 MHz in a $0.7 \times 0.7 \times 0.2$ inch size.

6 Claims, 5 Drawing Figures

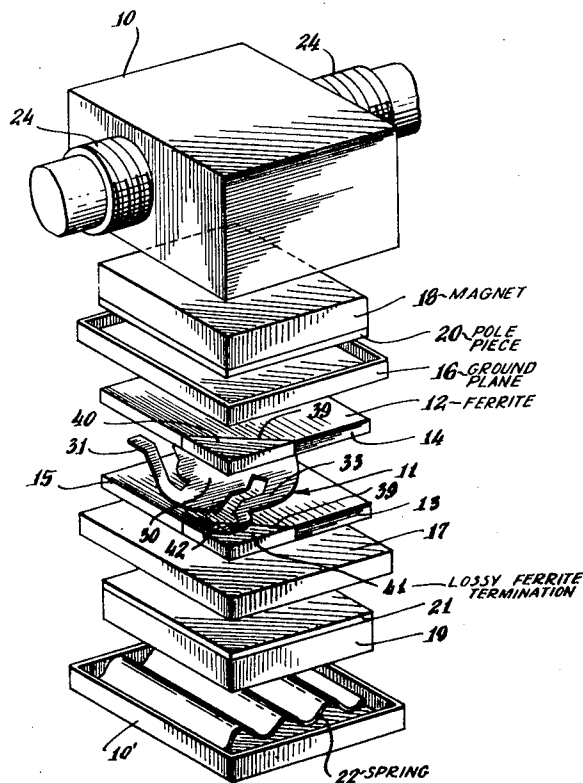


Fig. 2.

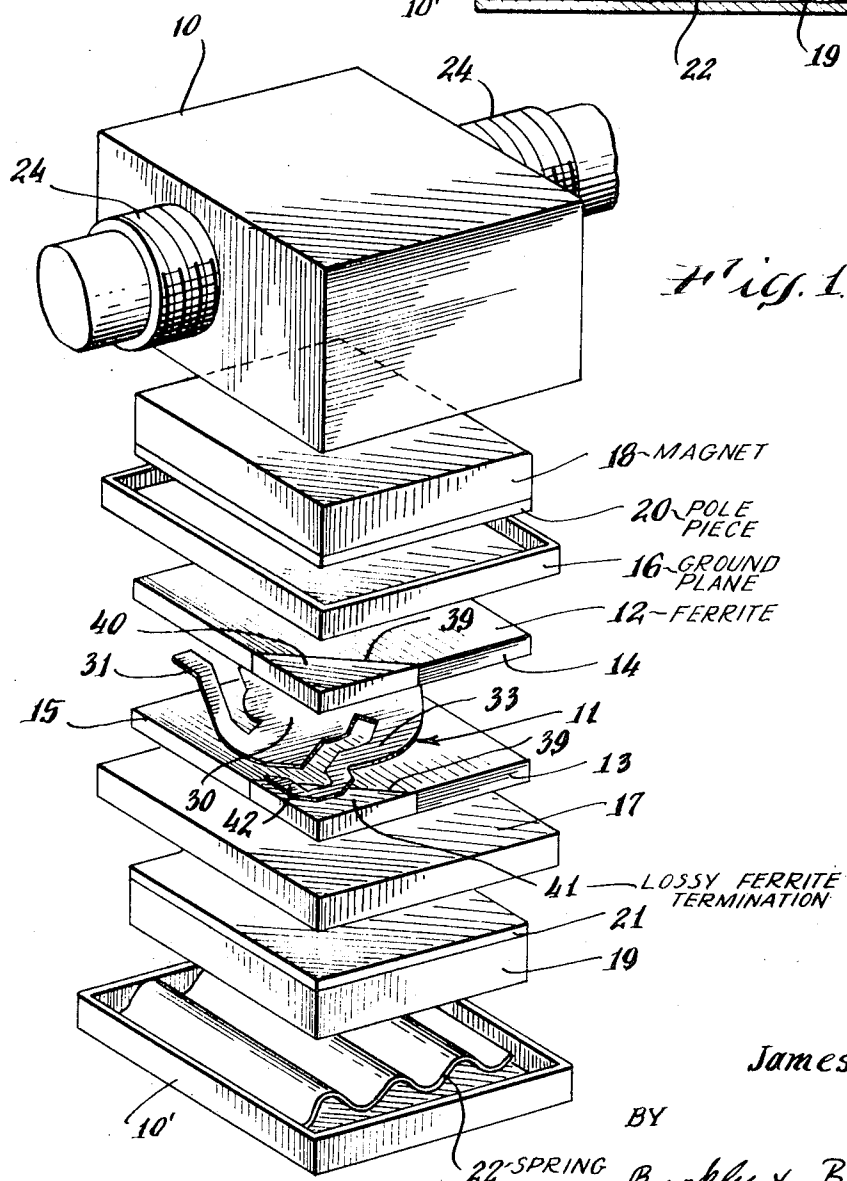
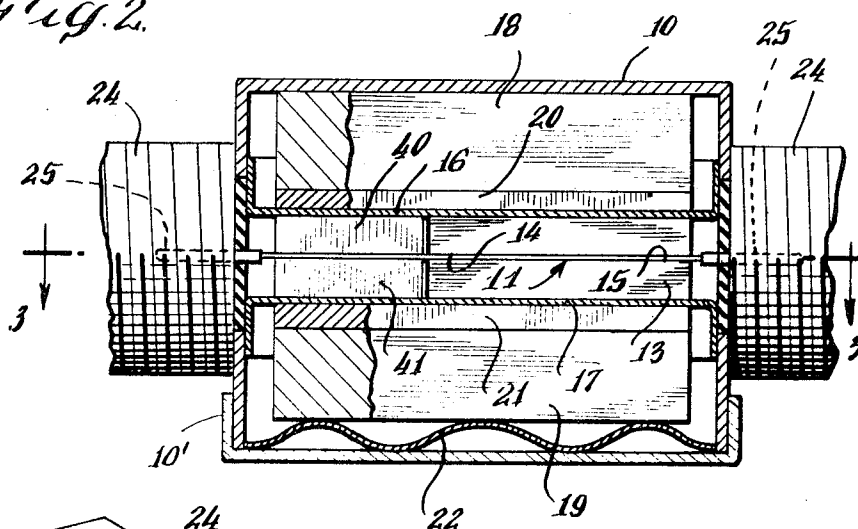
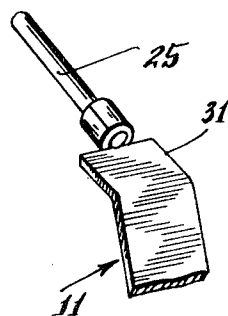


Fig. 1.

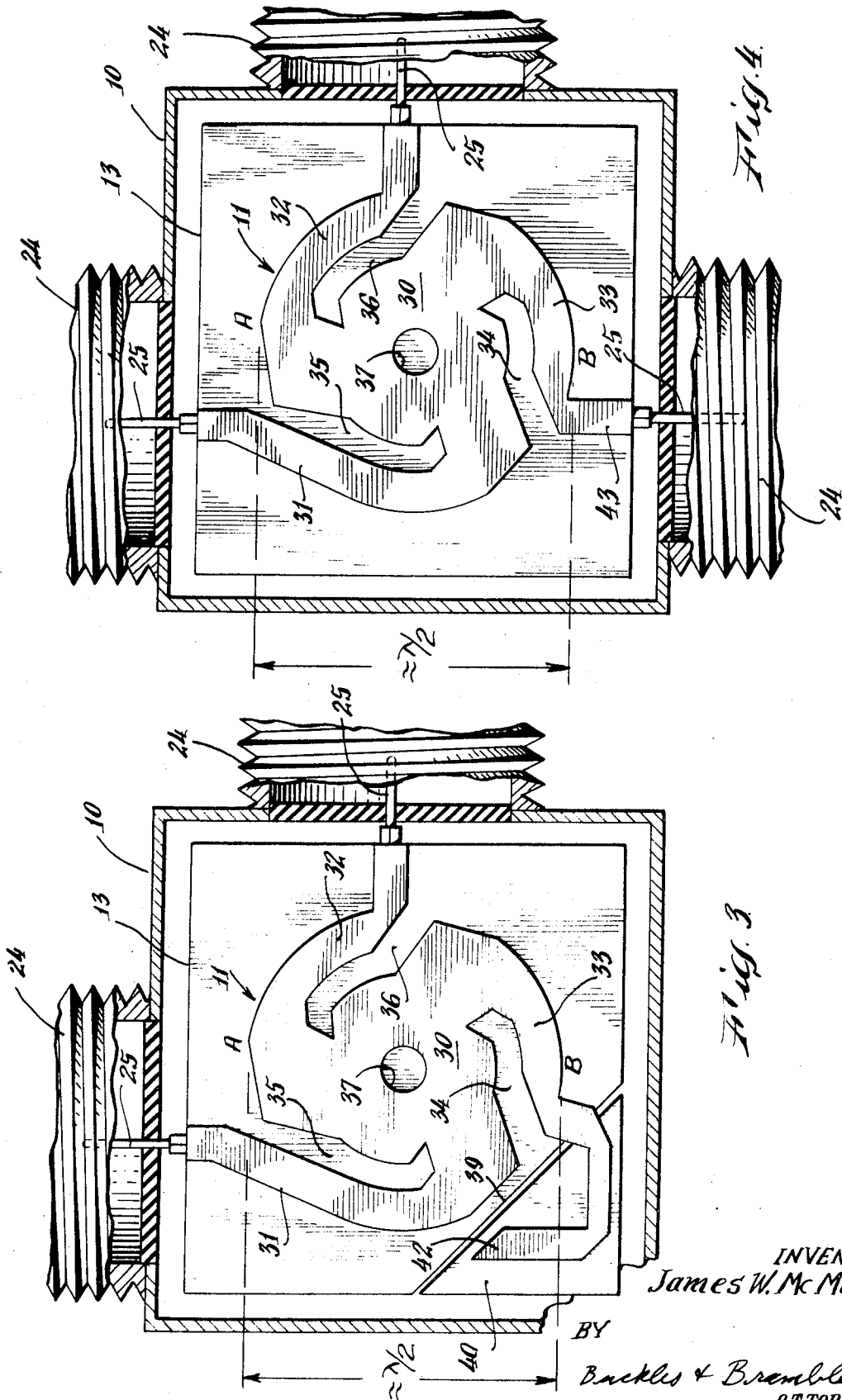
Fig. 5.



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MINIATURIZED FERRIMAGNETIC CIRCULATOR FOR MICROWAVES

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to miniaturized compact broad band microwave energy circulators of the strip line type capable of matching any desired impedance input or output lines without requiring external impedance matching transformers.

2. Description of the Prior Art

A simple microwave strip transmission line circulator was disclosed in U. S. Pat. No. 3,063,024 issued Nov. 6, 1962 to L. Davis, Jr. an article, "On the principles of strip line circulation" was published by H. Bosma in the Proceedings of the Institute of Electrical Engineers (London), vol. 109B, suppl. 21, pp. 137-146, Jan. 1962. The theories of operation and practical applications of circulators in the microwave field have been discussed in a series of articles by Dwight Caswell published in *Microwaves* in June, August and November of 1963, and in March 1965. A specific high power circulator for use in VHF and UHF bands has recently been disclosed by Yoshihiro Konishi in U. S. Pat. No. 3,551,852, and a broader band variation is disclosed in U. S. Pat. No. 3,551,853, both issued Dec. 29, 1970. In all of the prior art circulators employing ferrite materials as the circulator elements there has been the problem of matching the relatively low impedance of the ferrite elements to normally higher impedance input and output circuits. The importance of good impedance matching between the input source and the circulator, and between the circulator output port and the load, in order to obtain proper circulation and maximum isolation at the isolated port, was recognized by Caswell in the August 1963 issue of *Microwaves*. Heretofore in order to match the low impedance at the circulator ports to the normal 50 ohm transmission lines it has been necessary to employ impedance matching transformers between the circulator terminal ports and the connecting transmission lines. When such transformers were incorporated into the circulator package, as has been done, they rendered the overall circulator structure too large and cumbersome for many modern applications where emphasis is directed toward miniaturization of circuit components.

SUMMARY OF THE INVENTION

By the present invention I have discovered means whereby the requisite impedance transformation may be achieved entirely within the circulator structure itself without increasing the external physical dimensions of the complete circulator device. I accomplish this by forming the circulator port terminals of the central conductive plate as parti-circular, or spiral arms separated from the remainder of the central conductor plate by curvilinear slots whose width and depth are related to the impedance of the external line to be matched, while the overall diameter of the central conductive plate bears a constant relationship to a fraction of the wavelength at which the circulator is designed to operate. The complete impedance matching structure of the invention can be formed within the confines of the central conductive disk which may be of a diameter equal to $\lambda/2$, as discussed by C. E. Fay and R. L. Comstock in "Operation of the Ferrite Junction Circulator," IEEE Trans., Microwave Theory Tech. Vol.

MTT-13 pp. 15-27, Jan. 1965. I have also discovered that by providing an aperture in the center of the central conductive plate, of a diameter approximately equal to one tenth the overall diameter of the central conductive plate, I can reduce the frequency at which the circulator operates most efficiently or, conversely, I can reduce by ten percent the overall size of a circulator for any chosen frequency. The invention not only provides the required impedance match at all circulator ports but also reduces linear size of the circulator by a factor of 3, area by a factor of 8, and volume and weight by as much as 15 fold.

In an alternative embodiment of the invention a high loss ferrite attenuator may also be incorporated into the circulator and coupled to the odd port connector, where the lossy ferrite is magnetically biased to resonance by the same fixed magnets which influence the high mu ferrite circulator elements thereby providing internal termination of unwanted signals. Because of the intimate contact of the ground plane plates with the external steel housing, a heat sink is provided to dissipate substantial amounts of heat generated within both the ferrite circulator elements and the internal attenuator. Even in a device of only one half inch external linear dimension, as designed for S Band operation between 2.2 and 2.3 GHz, the internal terminator is capable of dissipating more than 10 watts power. The ferrite elements employed as terminators in the invention are capable of operation up to a Curie temperature of 585°C beyond which they simply do not absorb any more energy. Thus the device with internal attenuator is fail-safe in that it cannot self-destruct but will return to normal upon cooling, regardless of any degree of overheating.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an exploded perspective view of a circulator built according to the invention, drawn to an enlarged scale;

FIG. 2 is a vertical cross-sectional view of the assembled circulator of FIG. 1, drawn to a greater enlarged scale;

FIG. 3 is a horizontal cross-sectional view, partially broken away, taken along the center line 3-3 of FIG. 2 and even more greatly enlarged, showing a preferred two-port embodiment of a circulator according to the invention, having internal termination;

FIG. 4 is another horizontal cross-sectional view, similar to FIG. 3, showing a three-port embodiment of a circulator according to the invention; and

FIG. 5 is an enlarged perspective view of one terminal arm of the central conductive plate of the circulator of the invention, showing one method for connection to the external coaxial connectors of circulators fabricated according to the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring first to FIG. 1 of the drawing, which represents an enlarged exploded perspective view of the preferred circulator of the invention, the entire assembly is enclosed within an external steel housing 10 which mates with and is sealed to a bottom cover 10'. In the preferred embodiment the enclosure 10-10' is rectangular although it may as well be cylindrical if desired. Extending in a horizontal plane within the center of the housing 10 is a plane center conductor element 11

which is preferably of silver plated brass or beryllium. Adjacent opposite faces of the planar central conductor element 11 are a pair of ferrite elements 12 and 13, which may be formed from any of the well known ferrimagnetic ceramic materials which are low loss dielectric materials having a high relative magnetic μ . Yttrium iron garnet polycrystalline materials (YIG) are exemplary for this purpose. While the exploded view of FIG. 1 shows space between the upper ferrite element 12, and between the lower ferrite element 13, and the center conductor plate 11, solely for clarity of disclosure, it will be understood by those experienced in the art, and by reference to FIG. 2 of the drawings, that in the completed assembly the bottom plane face 14 of element 12 and the upper plane face 15 of element 13 are both in intimate contact throughout their surface areas with opposite faces of central conductor 11.

Adjacent to and in intimate contact with the upper plane surface of ferrite element 12 (as clearly shown in the assembled cross-sectional view of FIG. 2) is a ground plane conductive plate 16, while a corresponding conductive ground plane plate 17 is similarly in contact with the lower plane surface of ferrite element 13. Ground plane plates 16 and 17 may be formed of any suitable non-magnetic metallic conductor materials such as brass, copper, or aluminum. Adjacent to the opposite surfaces of ground plane plates 16 and 17 are a pair of fixed magnets 18 and 19. In the preferred embodiment of the invention the plane surfaces of magnets 18 and 19 which are adjacent ground planes 16 and 17 are faced with soft iron pole pieces 20 and 21, respectively, to facilitate more efficient dissemination of magnetic flux from magnets 18 and 19 through the ferrite elements 12 and 13. Between the magnet 19 and the external steel housing 10 a spring steel wafer 22 is positioned to maintain intimate pressure contact between adjacent parallel plane surfaces of all the elements 12 through 21 in the stacked assembly of the device as shown in FIG. 2. An external coaxial connector 24 is mounted on the outer wall of housing 10 and has a central conductor 25 which is insulatively passed through the wall of housing 10 and connected to a port terminal of center conductor 11, as will be described more particularly hereinafter with reference to FIGS. 3, 4 and 5 of the drawing. Normally two or three external connectors may be provided, depending upon whether the circulator device is designed for internal or external attenuation of power at a rejection port.

Referring now to FIG. 3 of the drawing which is cross-sectional plan view of the device taken along line 3-3 of FIG. 2, a preferred embodiment of the invention including an internal attenuator will be described with particular reference to the lower left-hand portion of FIG. 3. In this embodiment the high μ low loss ferrite material 13 has one corner portion removed along the line 39, and a corresponding chip of very lossy ferrite 40 which may be magnetically biased at resonance is substituted for this portion. Alternate materials suitable for the lossy ferrite chips 40-41 are those manufactured by Trans-Tech, Inc. of Gaithersburg, Md. and designated TT2-101, or the product manufactured by Xtalonix Products Division of Harshaw Chemical Co. of Columbus, Ohio, designated as NF-3000 ferrite. The terminal arm 33 of center conductor element 11 is extended in an angular configuration 42 adjacent to and in intimate contact with the plane surface of lossy chip 40, and the external connector terminal 43 (shown in

FIG. 4) is eliminated. The terminator arm 42 in FIG. 3 is sandwiched between upper and lower triangular chips of high loss ferrite material 40 and 41, as shown in FIG. 2. The same permanent magnets 18 and 19 (FIG. 2) which bias the high μ ferrite material 12 and 13 to produce circulator action within the area of central conductor 11 defined by the diameter A-B also serve to bias the high loss ferrite material 40 and 41 into resonance at the microwave frequency for which the device is designed. In this manner the unwanted microwave energy appearing at circulator arm 33 is dissipated and absorbed as heat generated within the high loss ferrite chips 40 and 41. Because of the good heat conductivity of the metallic ground plane plates 16 and 17 which are in intimate contact with the opposite plane surfaces of the attenuator ferrite chips 40 and 41, and also in heat conductive contact with the internal walls of the outer steel housing 10-10', the internal heat generated within the attenuator chips is rapidly transmitted to and dissipated by the substantial heat sink formed by the outer steel housing 10-10'. Thus the need for a separate attenuator external to the circulator, as has been required in the prior art, is effectively eliminated in the device of the present invention. The high loss ferrite chips 40 and 41 are capable of operating as energy absorbers in their resonant circuit at Curie temperatures up to 585°C. If they should be overloaded by the application of energy sufficient to raise their temperature beyond this point, then they merely cease to absorb additional energy and at this temperature the device ceases to perform efficiently. However, upon cooling to any temperature below the Curie point the previously overheated device returns to its normal operation, and thus devices made according to this disclosure are incapable of self-destruction due to internally generated heat.

Reference is now had to FIG. 4 of the drawing which is a cross-sectional plan view of another embodiment of the device, showing a three-port circulator according to the invention. In the plan view of FIG. 4 the central conductor element 11 is seen to be formed of a solid central portion 30 surrounded by three spirally radiating arms 31, 32 and 33. Slotted portions 34, 35 and 36 of central conductor 11 are removed as shown in this view to form transformer sections between the spiraled conductive arms 31, 32 and 33 and the central conductive portion 30. The length and location of the cutaway slots 34, 35 and 36, and consequently the length and impedance of the spiral conductive arms 31, 32 and 33 produced thereby, determines the length and impedance of the coupling transformer between the coaxial connector terminals 4-25 and the central conductive portion 30 which forms the circulator with ferrite elements 12 and 13. The deeper the slots penetrate toward the center 30, and the wider the remaining spiral arms 31, 32 and 33 are, the lower will be the impedance of the transformer between the external connector terminals 25 and the central conductor portion 30. The drawing of FIG. 4 is drawn to scale (greatly enlarged) and shows the configuration of a preferred circulator central conductor plate 11 as designed to match a circulator impedance of approximately 10 ohms to an external transmission line of fifty ohms. If it were desired to match a circulator according to the invention to a thirty ohm line, for example, the slots 34, 35 and 36 would be made further from the edge of the disk as shown in FIG. 4, while if it were desired to match the

circulator to a higher impedance line such as, for example, a 75 ohm transmission line, then the slots 34, 35 and 36 would be closer to the edge of the disk in a spiral surrounding the central portion 30 and thereby making the conductor arms 31, 32 and 33 narrower than shown in FIG. 4; and hence of higher impedance.

As taught by prior workers in the circulator art, including Fay and Comstock of Bell Telephone Laboratories, the diameter of a circular central conductor plate should equal one half the wavelength of energy to be circulated. In the present invention I have discovered that the integrity of this optimum circulator diameter may be maintained even when impedance matching spiral slots such as 34, 35 and 36 are cut into the circulator disk. Thus in the circulator of the invention the operative circulator diameter between points A and B of FIGS. 3 and 4 is equal to $\lambda/2$ while the desired impedance matching to the external ports is achieved by cutting the spiral slots 34, 35 and 36 within the boundary of the central conductor's outside diameter, without any perceptible adverse effect on the circulator's efficient operation at any desired microwave frequency.

I have also discovered that by piercing the central portion 30 of central conductor 11 with a non-conductive aperture or circular hole 37, as shown in FIGS. 3 and 4, I can reduce the effective frequency at which a circulator of any given size operates most efficiently or, conversely, I can reduce the overall size of a circulator for any chosen frequency of operation. Experimental results have provided an empirical rule that the central aperture 37 may be of a diameter up to and including one tenth of the disk diameter, A-B in FIGS. 3 and 4 and that an aperture of these dimensions enables a reduction of frequency and/or physical size by 10 percent. Thus by combining my spirally cut impedance matching slots 34, 35 and 36 with the central aperture 37 in the central conductor shown generally at 11 in FIGS. 3 and 4, I am able to produce efficient microwave circulators for L and S bands, operating from 1.435 GHz to 1.535 GHz, and 2.2 - 2.3 GHz, respectively, within an overall configuration of only three-fourth inch square by $\frac{1}{2}$ inch height. By the same techniques I have produced a P-Band circulator operating at 975 MHz with 2 percent bandwidth, within an overall configuration of only 0.7 inch square by 0.200 inch height.

FIG. 5 shows in detail the manner in which the center terminal conductors of external coaxial connectors are connected to the ends of the circulator port arms. The ends of these arms are simply rolled over and tightly crimped around the end of the terminal conductor wire. While it would be theoretically desirable to solder these external connections, because of the extremely small size of these devices no way has yet been found to effect a soldered connection. However, with firmly crimped connections as shown the devices have been found to perform their circulator function quite efficiently.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above construction without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawing shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention which, as a matter of language, might be said to fall therebetween.

Having described my invention, what I claim as new and desire to secure by Letters Patent is:

1. In a microwave circulator having a high Mu ferrite element with opposed parallel plane surfaces, a metallic ground plane conductor plate in intimate contact with one plane surface of said ferrite element and a generally circular center conductor plate in intimate contact with the opposite plane surface of said ferrite element, the combination wherein said center conductor plate is formed with a plurality of peripheral arms extending spirally from within said generally circular conductor plate, said arms extending generally non-radially from said center conductor plate beyond the mean diameter thereof in contiguous overlying engagement with extending portions of said high Mu ferrite element means connecting the extremities of at least two of said arms with external electrical terminals, and a permanent magnet in intimate contact with the surface of said ground plane conductor plate opposite said ferrite element.

2. The combination of claim 1 including a high loss ferrite element within the field of said permanent magnet and having opposed parallel plane surfaces in intimate contact with said ground plane plate and a peripheral end extension of one of said spiral conductor arms.

3. The combination of claim 1 characterized by a doubledeck sandwich configuration wherein said center conductor plate is bounded on opposite faces thereof by a pair of high Mu ferrite elements, the opposite parallel plane surfaces of both said ferrite elements are in intimate contact with separate ground plane plates, and a pair of permanent magnets form the top and bottom of the sandwich structure, each of said magnets having a plane surface in intimate contact with the surfaces of said ground plane plates opposite said ferrite elements.

4. The combination of claim 1 wherein the mean diameter of said generally circular conductor plate approximately equals one half the wavelength of microwave energy to be circulated, and said spirally extending peripheral arms are formed between spiral slots extending into said center conductor plate within the mean diameter thereof, whereby the coupling between each of said spiral arms and said ground plane conductor through said ferrite dielectric forms a transformer to match the low impedance of said ferrite circulator element to a higher impedance external transmission line.

5. In a microwave circulator having a pair of high Mu ferrite elements adjacent and overlying opposite plane surfaces of a substantially circular central conductor plate, the mean diameter of said central conductor plate being approximately equal to one half the wavelength of microwave energy to be circulated, and means for establishing a magnetic field substantially orthogonal to the planes of said ferrite elements and said conductor plate, the combination comprising, means defining a plurality of slots formed in said central conductor plate extending from the periphery thereof spirally inward toward the center thereof, a corresponding plurality of conductive arms remaining between said slots within said mean diameter, said arms extending generally non-radially from said central conductor

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plate beyond the mean diameter thereof in contiguous overlying engagement with extending portions of said high Mu ferrite elements, means connecting the extremities of two of said conductive arms to external electrical terminals, and a pair of lossy ferrite elements adjacent opposite surfaces of an extension of a third arm and located within said magnetic field whereby said lossy ferrite elements are biased to resonance at the frequency of microwave energy to be circulated.

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6. The combination of claim 5 characterized by a central aperture formed in said center conductor plate, the diameter of said aperture being approximately one tenth the mean diameter of said center conductor plate, whereby the optimum frequency for operation of said circulator is reduced below the optimum frequency thereof without said aperture.

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