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Vittoria et al.

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[54] **DOUBLE-CAVITY MICROWAVE FILTER**

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

[51] **Int. Cl.**..... **H01p 1/20;** H01p 7/06

[58] **Field of Search**..... 333/73 W, 73 R, 24.2, 73 S, 333/76, 83 R, 24.1

[56] **References Cited**

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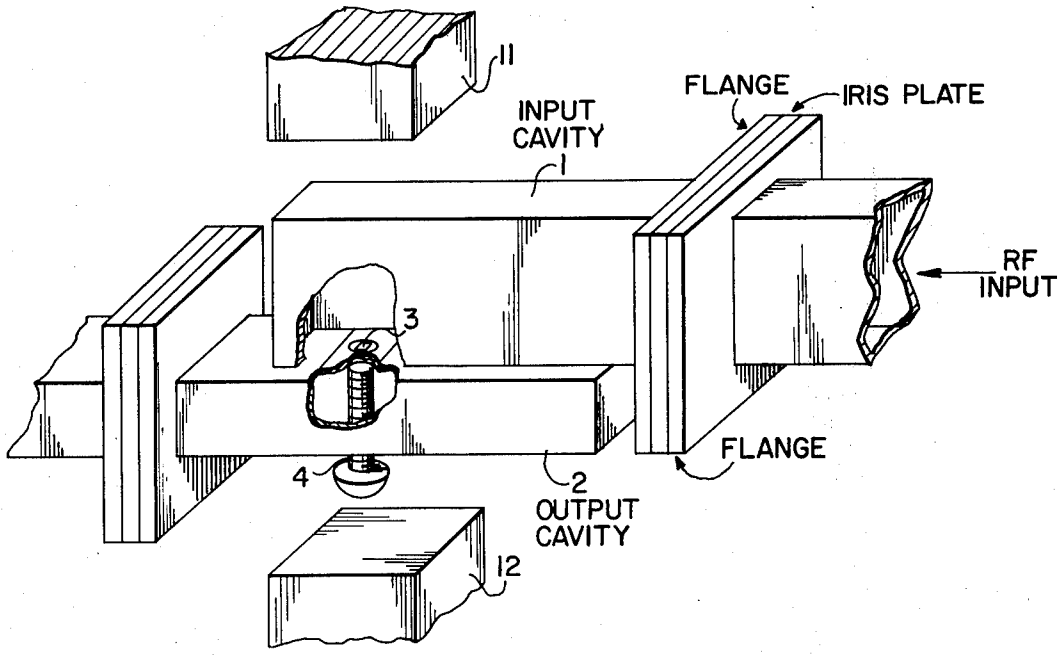
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[57] **ABSTRACT**

An improved magnetically tunable band-pass filter for use in the microwave regions, particularly at X-band and beyond. Two waveguides are adjacently positioned to form a double cavity arrangement such that the radio-frequency (RF) magnetic fields in each cavity are orthogonal to one another. A substrate, having thin-film layers of ferrimagnetic material deposited on opposed parallel surfaces, is positioned in an opening between the adjacent cavities so that one of the layers is positioned in each cavity to form a coupling resonator. An external direct current (DC) magnetic bias field is then applied in a direction normal to the input RF field and controlled in angle relative to the surface of the ferrimagnetic material. For any given magnitude of the magnetic bias field, the resonance and, thus, the bandpass of the filter, is adjusted over a wide range of frequency by varying the angle of the magnetic bias field relative to the noted surface.

11 Claims, 2 Drawing Figures



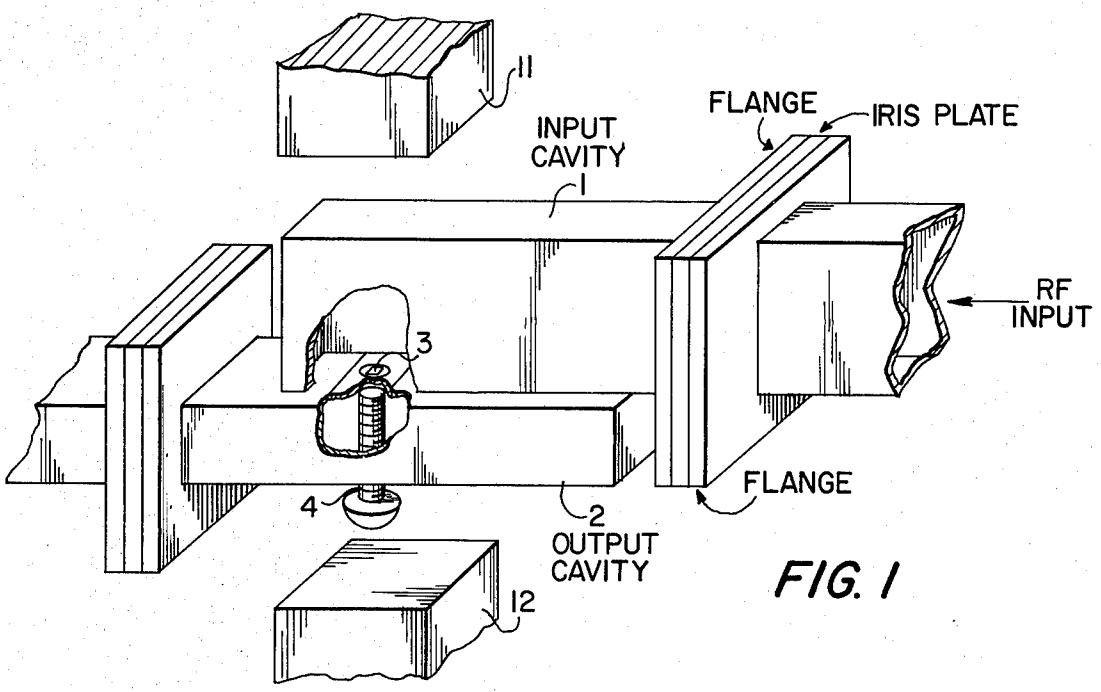

11
INPUT CAVITY
1
FLANGE
IRIS PLATE
RF INPUT
3
4
2
OUTPUT CAVITY
FLANGE
12

FIG. 1

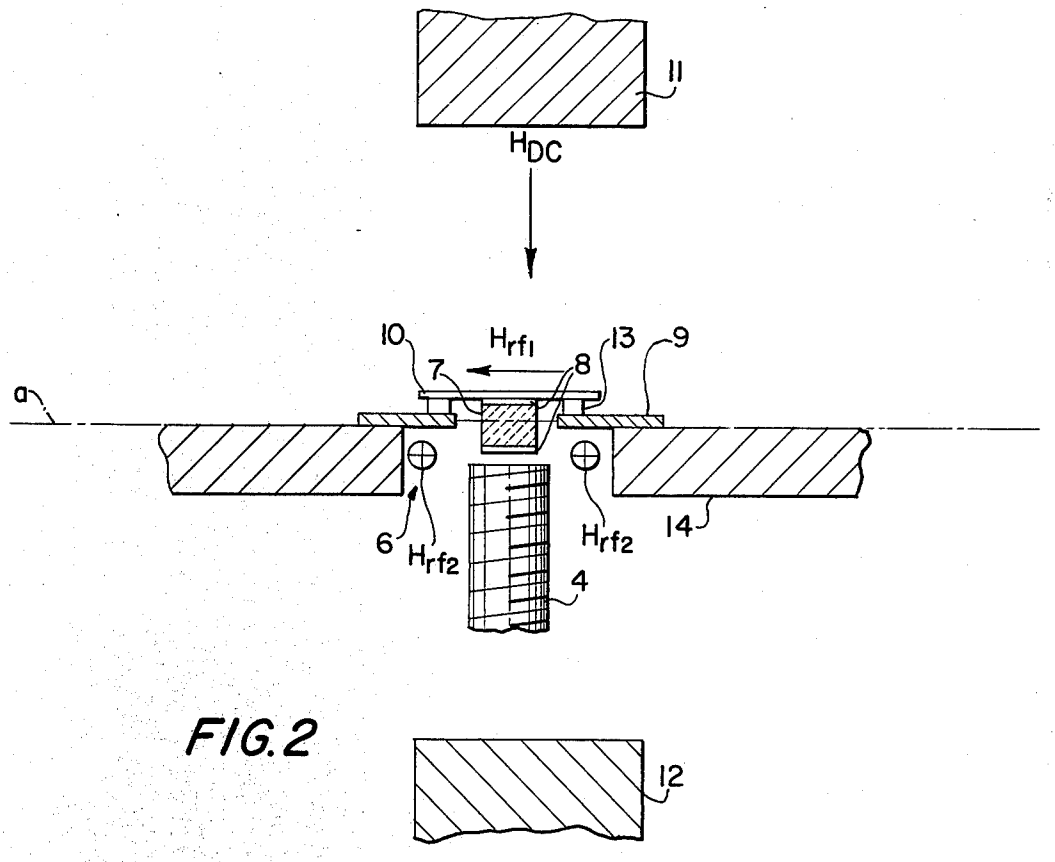

11
H_{DC}
10
H_{rf1}
13
9
7
8
a
6
H_{rf2}
H_{rf2}
14
4
12

FIG. 2

DOUBLE-CAVITY MICROWAVE FILTER

BACKGROUND OF THE INVENTION

The present invention relates to improved magnetically tunable filters and more particularly to magnetically tunable band-pass filters operating in the microwave region and utilizing ferrimagnetic resonators.

In the field of electrical filters, band-pass filters are of particular importance in many diverse electrical systems where it is desired to pass certain frequency bands with high selectivity over a wide range of frequency. In certain areas of communication systems it is frequently desirable to have filters that exhibit the above selectivity and in addition are capable of switching between frequency bands in a relatively rapid manner while retaining a high coupling efficiency over the wide range of frequency. It has also been desirable to be able to construct the filters with only simple modifications to known waveguide structure in order to reduce the complexity and still maintain low cost and high quality operation. In accomplishing the above objects prior known techniques have met with limited success resulting in filters having less than optimum operational characteristics, particularly in the X-band of the microwave region.

In one known prior art technique according to U.S. Pat. No. 3,268,838, adjacent waveguides are coupled through specially aligned slots by a pair of yttrium-iron-garnet (YIG) resonator spheres. While the band-pass of this type filter can be controlled by adjusting the resonance of the coupling spheres with a magnetic bias field, the structure has been only partially successful in providing optimal filter conditions. The use of YIG spheres, for example, limits the range of adjustment to a very narrow region and requires a specially reduced waveguide section to increase coupling efficiency. Even with this special configuration, problems are encountered with spurious response due to the proximity of the metal walls of the waveguide. While the range of operation and quality of response may be extended by changing the dimensions of the spheres, the material of the spheres, or the physical construction of the waveguide, such limitations do not allow much flexibility in filter operation.

In other known techniques, single resonator configurations have suffered from similar restrictions while requiring additional mechanical mounting structure and special auxiliary equipment. In particular, YIG disk resonators formed as "bulk" films or as single crystals, have been used to construct a filter in a manner similar to the above mentioned patent. However, special mounting and alignment requirements have been necessary to give only a limited response over a restricted range of frequency. In addition, the bulk and crystal devices tend to have unfavorable aspect ratios (generally, sample diameter or lateral dimension ÷ thickness) which cause non-uniform characteristics and unpredictable results in filter operation. Particularly significant are limitations on coupling efficiency, band definitions and range and ease of frequency adjustment.

With the advent of chemical vapor deposition (CVD) and liquid-phase epitaxy (LPE) technologies, it has been possible to obtain high quality YIG films for microwave use. Bandstop and band-pass filters in the 2GH range have been developed using single YIG disks epitaxilly evaporated on gadolinium-gallium-garnet (GGG) substrates. However, even with such improved

devices, there has been little success with operations in the X-band (8-12.5 GHz) and beyond, and relatively little success in achieving increased adjustment capability over an extended frequency range.

Accordingly the present invention has been developed to overcome the specific shortcomings of the above known and similar techniques and to provide a filter having fewer elements while still providing more reliable and versatile operational characteristics.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an improved filter which is simple and inexpensive in construction and tunable over a relatively wide range of frequency.

Another object of the invention is to provide a filter having improved and reproducible response characteristics for operation in the microwave region, particularly in the X-band.

A further object of the invention is to provide a band-pass filter using thin film ferrimagnetic resonators.

Still another object of the invention is to provide a magnetically tunable filter whose response characteristics can be varied by changing the orientation of a magnetic field.

Yet another object of the invention is to provide a band-pass filter wherein the passband is centered at resonance and which provides high coupling and low insertion loss within the pass-band and relatively high rejection outside the pass-band.

In a typical embodiment of the invention, the above objects are accomplished by positioning the end cavities of two X-band waveguides adjacent to one another, and orienting the cavities such that microwave energy introduced into the input section will have an RF magnetic field direction orthogonal to the RF magnetic field direction in the output cavity. An opening, provided in the adjacent walls of the cavities, will not normally couple energy from the input waveguide to the output waveguide due to the orientation of the cavities. The two cavities are coupled, however, by inserting a ferrimagnetic resonator into the opening. The resonator according to the invention, is formed by depositing highly reproducible films of YIG on opposed parallel surfaces of a GGG substrate by well known CVD and LPE techniques. In the filter structure, one of the films is positioned in each of the cavities and oriented such that the input RF magnetic field direction is parallel to the film surface. An external DC magnetic bias field is then applied in a direction normal to the input RF magnetic field direction and made adjustable in angle relative to the film surface. By fixing the magnitude of the bias field and varying the angle α relative to the film surface, the frequency of resonance, and, thus, the frequency of transmitted energy, can be adjusted for angles of α ranging from $0° < \alpha < 90°$. Such adjustment can be made to vary the frequency over a range of 8–15 GHz, for example. An additional coupling screw can be inserted into the proximity of the YIG surface in the output cavity and adjusted to maximize coupling of microwave energy between the two cavities.

Other objects, advantages and novel features of the invention will become apparent from the following detailed description of the invention when considered in connection with the accompaning drawings wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a particular embodiment of the invention illustrating the basic arrangement of the elements for forming a microwave filter.

FIG. 2 is a detailed diagram showing a partial cross sectional side view of the resonator-coupling arrangement used in the filter of FIG. 1.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, a band-pass filter constructed according to the present invention is shown having an input portion 1 and an output portion 2. The input and output portions are formed as first and second cavities constructed from shorted end sections of X-band rectangular waveguides. The input and output cavities are designed to receive microwave energy as RF input from the input waveguide, and transmit energy to output circuitry by way of a connecting waveguide from the output cavity. The shorted end cavities are positioned in adjacent overlapping relationship and provided with a connecting passage 6 between the two cavities. The connecting passage 6 is located at the point of maximum amplitude of the RF magnetic fields and with the opening in the input cavity located where the field (H_{rf1}) is parallel to the length of the cavity.

In this particular example the adjacent waveguide walls were machined to provide a common wall, generally illustrated at 14, having a 0.05 inch thickness and a 0.100 inch diameter hole forming the connecting passage 6. The cavities are arranged so that the RF magnetic fields (H_{rf1}, and H_{rf2}, FIG. 2) on each side of the adjacent walls are orthogonal to one another to prevent direct coupling of the RF energy through the connecting passage 6. A flange and iris plate structure is located in each waveguide section, as shown in the drawing, to allow adjustment for maximum voltage transmission through the cavities in a manner well known in the art.

Positioned in the connecting passage 6 is a ferrimagnetic resonator sample 3. The sample, as shown in FIG. 2, is of double layer configuration formed from a substrate 7 having two opposed parallel surfaces on each of which is deposited a uniform ferrimagnetic film 8. In the present example the substrate 7 is composed of gadoliniumgallium- garnet (GGG) but may be of any material capable of supporting the ferrimagnetic film which in the present example is yttrium-iron-garnet. The film layers are 2μ in thickness although the thickness can be varied to give a high aspect ratio as will be later explained. The films are preferably deposited using well known chemical-vapor-deposition (CVD) or liquid-phase-epitaxy (LPE) techniques an example of which is described in the article "Magnetic Oxide Films," IEEE Trans. Magnetics MAG-5, 717 (1969).

In the present configuration, even with the ferrimagnetic sample 3 positioned in the passage 6, very little leakage or coupling occurs between the input and output cavities due to the orthogonal arrangement of the adjacent RF magnetic field components. However, according to the present invention, coupling can be controlled by utilizing particular characteristics of the ferrimagnetic sample 3. The resonance characteristics of ferrimagnetic materials are well known and will therefore not be discussed in great detail. Generally however, ferrimagnetic materials display resonance at a frequency which will be dependent on the magnitude of a DC magnetic bias field applied to the material as exampled in U.S. Pat. No. 3,268,838. By varying the magnitude of the field, the frequency at which resonance occurs can be adjusted over a range of frequencies. In film materials (contrasted with YIG spheres), as is known in the art, resonance frequency depends not only on the magnitude of the DC field, but also on the direction of the field relative to the surface of the film. Thus, even when a constant magnitude DC magnetic field is applied to a film of ferrimagnetic material, the frequency of resonance can be varied solely by changing the angle of the magnetic field relative to the surface of the film.

Turning again to FIG. 1, the above double layer resonator structure 3 is positioned in the passage 6 and the cavities positioned between the poles 11 and 12 of an electromagnet. The electromagnet is designed to provide an adjustable and relatively uniform DC magnetic field directed onto the entire surface of the ferrimagnetic material of sample 3, in a direction normal to the direction of the input RF magnetic field direction H_{rf1}. In addition, the electromagnet is constructed in any conventional manner to enable the poles to be rotated about an axis a extending through the center of the sample and parallel to the length of the waveguide so that rotation of the poles allows the DC magnetic field direction to be varied relative to the film surface over at least an angle α of $0° < \alpha < 90°$ where 90° is normal to the surface and 0° is parallel to the surface.

The sample itself is positioned in the passage 6 such that one film is positioned in each of the cavities and the film surfaces are substantially parallel to the adjacent walls of the waveguide (FIG. 2). In the present example the substrate 7 had dimensions of 0.02 in. thickness by 1mm × 1mm compared to a wall thickness of 0.05 in. A 5 mil(or 125μ) brass shim 9 was therefore inserted to form part of the common wall for mounting the sample 3. The sample was attached to a piece of mica 10 (using a light grease) which in turn was mounted on several Teflon pieces 13 to form a bridge whose height allowed a YIG film to be positioned in each cavity. While the special arrangement was necessary for the particular sample used, it is obvious that other mounting techniques could be employed for samples and waveguides of different dimensions provided that the end result is a film positioned in each cavity at the point of maximum amplitude of the RF magnetic fields.

The above configuration can now be operated as a band-pass filter, according to the present invention, utilizing the resonant characteristics of the ferrimagnetic materials as previously described. The magnitude of the applied DC magnetic field (H_{DC}) is set at a constant value and the input waveguide coupled to receive the RF energy to be filtered. For energy of frequencies other than those causing resonance in the film, there will be only a very low leakage coupling of the input and output cavities. However, for energy having a frequency for which the film displays resonance, the energy will be coupled by the double layer sample 3 to the output cavity. The bandwidth of the frequencies passed will be a band centered on the resonant frequency. This center frequency can then be adjusted by varying the angle α of the DC magnetic field between 0° and 90° for a constant value of the magnetic field. Naturally, by changing the magnitude of the DC field, a different

range of adjustments can be realized for variations in the angle of the DC field.

Using the particular waveguide and double layer configuration according to the present invention, improved coupling and increased frequency variations can be achieved over a wider range of frequencies, particularly the X-band frequencies, where the prior art has met with limited success. For example, with a DC field (H_{DC}) of 4500 Oersteds, the present filter can be turned with high selectivity over a range of 8–15 CHz and beyond by varying the angle α of the DC field relative to the film surface **8** between 0° and 90°. The double film configuration was found to provide sharp resonance with improved coupling efficiency. The value of coupling on-resonance was found to be an excellent 95–100 times greater than the coupling off-resonance, which off-resonance coupling was generally found to be relatively constant over all angles of α. Maximum coupling was found to occur at an angle $\alpha = 72°$ with a minimum insertion loss of 32dB. In addition, by way of example, for a center frequency of 9GHz, the filter was found to have a bandwidth of 6MHz and a loaded Q of 1500 for the YIG films used. With the advent of narrow linewidth YIG films deposited by LPE techniques, it is expected that the coupling ratio and insertion loss can be even further improved.

As was noted previously, the aspect ration of the film should be maintained at a high value. This is required since the range of adjustment and the band selectivity under the control of the DC magnetic field, are largely dependent on the aspect ratio of the film, generally exhibiting more favorable characteristics as the value of the aspect ratio increases. Using improved CVD and LPE techniques, it is possible to obtain the required aspect ratios to provide highly selective tuning over the entire X-band, while at the same time reducing the physical requirements (e.g. dimensions and auxiliary structure) of the filter itself. Compared to a YIG sphere having an aspect ratio of **1** where little or no adjustment can be obtained by varying the DC field angle, films deposited by CVD and LPE techniques and having aspect ratios much greater than **1** (100–1000 for example), will provide a very wide and selective range of tuning. By way of example, a sphere subjected to a 2000 Oersted field can only be tuned slightly away from a resonant frequency of about 6GHz while a filter using a film according to the present invention can be tuned over a range of ½ to 8GHz using the same 2000 Oersted field. Thus the capabilities of the present double layer configuration extend not only to the X-band region but to a wide variety of other ranges of frequency rendering the filter structure highly versatile.

In addition to the previously described structure, the present invention incorporates a coupling screw **4** to further improve the coupling characteristics of the filter. A one-thirtysecond in. diameter brass screw was inserted into the output cavity and made adjustable along an axis normal to the surface of the film **8** (FIG. **2**). By adjusting the spacing between the end of the screw and the film surface, the coupling at resonance can be maximized.

The filter device of the present invention was tested in a particular configuration where the input cavity was excited by a 9.02 GHz input frequency developing a TE_{104} mode in the input cavity and a TE_{102} mode in the output cavity. A crystal detector connected to the output waveguide measured the coupling voltage as the DC magnetic field direction and magnitude were varied. The YIG films were positioned at $\lambda/2$ from the shorted end of the input cavity and λ from the shorted end of the output cavity at the point of maximum RF magnetic field (H_{rf1} and H_{rf2}) for the particular modes generated. The coupling screw was adjusted to give maximum transmitted voltage without the application of the DC magnetic field. It was found that resonance occured for nearly all angles of α of the range of $0° < \alpha < 90°$ for different values of the static DC field at the 9.02 GHz frequency. As is well known, this is equivalent of using a fixed amplitude DC field and tuning the filter by changing the angle between the DC field and surface of the YIG film, where the film is magnetized for all values of α.

As can be seen from the above description, the present invention provides a relatively simple and inexpensive microwave filter that does not require special auxiliary equipmemnt or waveguide configurations, yet allows for versatile operation in a quick and efficient manner. In addition, as was previously noted, the double layer configuration employs improved CVD and LPE deposition techniques which provide additional benefits in construction and operation. Not only are the filter characteristics improved by use of the above CVD and LPE techniques, but the deposition methods lend themselves to highly reproducible microcircuitry techniques which result in filters of lower cost and more predictable characteristics over filters using mechanically formed garnet resonators of the prior art.

While the present invention has been described with particular reference to use with microwave waveguides, it is evident that the same principles can be applied to filters at lower frequencies, for example, with striplines. In addition, while the invention has been described with reference to particular dimensions the same could be varied (under different conditions) in a manner consistent with the teachings of this invention.

A further modification that can be made to the filter structure of FIG. **1** is the incorporation of an adjustable shorted end section in output cavity **2**. The adjustable short could be used to permit tuning of the output cavity to the resonant frequency of the input cavity. Such adjustment tends to increase the coupling ratio (coupling on-resonance to coupling off-resonance) by a factor of **2** but is not essential to the performance of the improved filter as described.

Obviously many other modifications and variations are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed and desired to be secured by Letters Patent of the United States is:

1. A magnetically tunable band-pass filter comprising:

a first microwave input portion for receiving microwave energy;

a second microwave output portion for transmitting microwave energy, said first and second portions being mounted adjacent to one another and connected by an opening therebetween;

a ferrimagnetic resonator positioned in said opening and comprising a substrate having opposed parallel surfaces with a ferrimagnetic material deposited uniformly over said opposed surfaces, said resonator being positioned such that one of said surfaces

extends into said input portion and the other into the output portion; and

magnetic means for applying a magnetic field to said resonator and varying the angle of the field relative to the surface of said ferrimagnetic material.

2. The apparatus of claim **1** wherein said input and output portions are formed from a pair of shorted end waveguides mounted in adjacent overlapping relationship having a connecting passage as said opening therebetween.

3. The apparatus of claim **2** wherein the waveguides are oriented such that the radio frequency magnetic field components in the input and output waveguides are orthogonal to one another to prevent direct coupling of energy through the passage.

4. The apparatus of claim **1** wherein the substrate is formed from gadolinium-gallium-garnet and the ferrimagnetic material from yttrium-iron-garnet.

5. The apparatus of claim **1** wherein the resonator is so positioned in said opening that the surface of the ferrimagnetic material in the input portion is substantially parallel to the direction of the magnetic field component of radio frequency energy.

6. The apparatus of claim **5** wherein the means for applying said magnetic field applies a DC field in a direction normal to the direction of the magnetic field component of radio frequency energy in the input portion.

7. The apparatus of claim **6** wherein the means for varying the DC magnetic field varies the DC field over an angle of at least 0° to 90° relative to the surface of the ferrimagnetic material.

8. The apparatus of claim **1** further including a means positioned adjacent the surface of said ferrimagnetic material in the output portion for increasing the coupling through said resonator.

9. The apparatus of claim **8** wherein said means comprises a coupling screw adjustably mounted along an axis normal to the surface of said ferrimagnetic material.

10. The apparatus of claim **1** wherein the ferrimagnetic material has an aspect ratio of 100–1000.

11. A magnetically tunable band-pass filter comprising:

a first microwave input portion for receiving microwave energy;

a second microwave output portion for transmitting microwave energy, said first and second portions being mounted adjacent to one another and connected by an opening therebetween;

a ferrimagnetic resonator positioned in said opening and comprising a substrate having opposed parallel surfaces with a ferrimagnetic material deposited uniformly over said opposed surfaces, said resonator being positioned such that one of said surfaces extends into said input portion and the other into the output portion; and

magnetic means for applying a variable magnitude magnetic field to said resonator.

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