April 16, 1968 D. R. JACKSON ETAL 3,378,760

REACTANCE-COMPENSATED PARTICLE-RESONANT, FREQUENCY-SELECTIVE LIMITER

Filed May 27, 1966 4 Sheets-Sheet 1

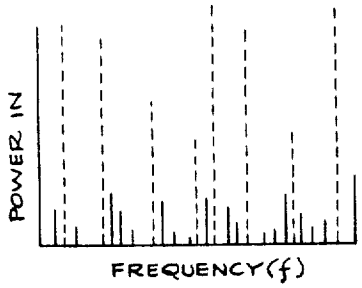


Fig. 1.

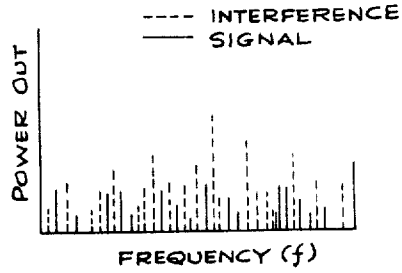


Fig. 2.

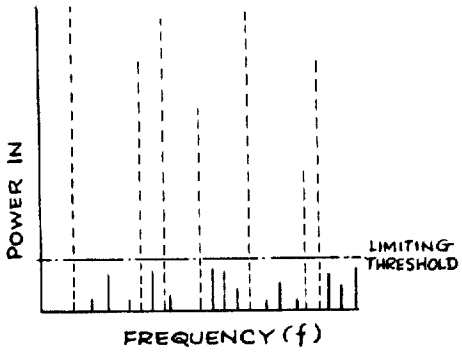


Fig. 3.

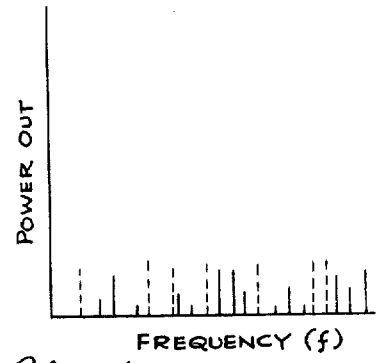


Fig. 4.

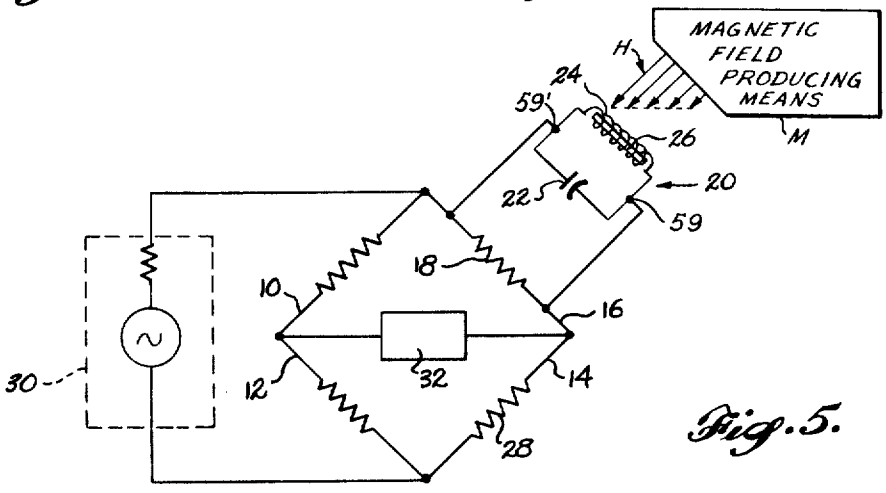


Fig. 5.

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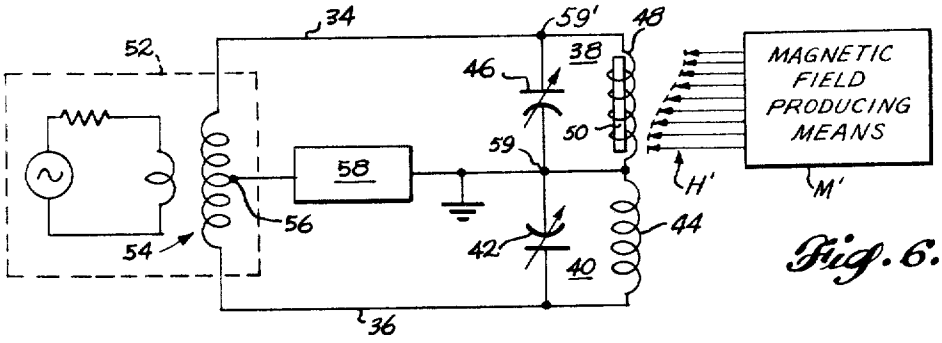


Fig. 6.

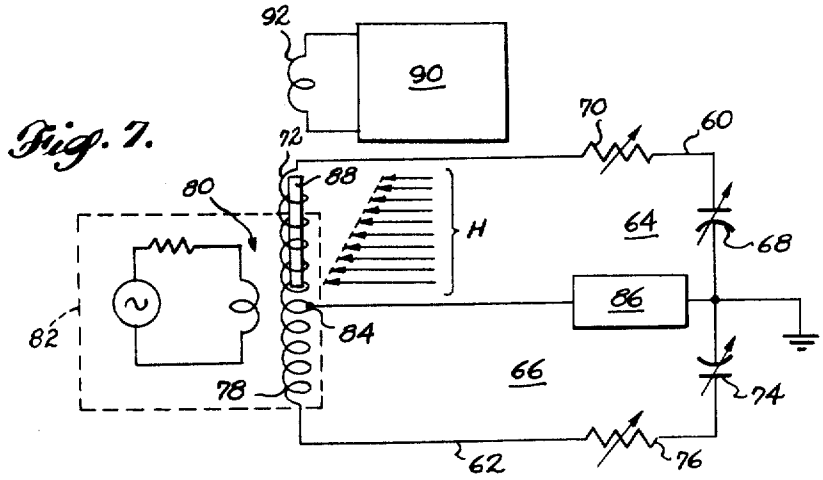


Fig. 7.

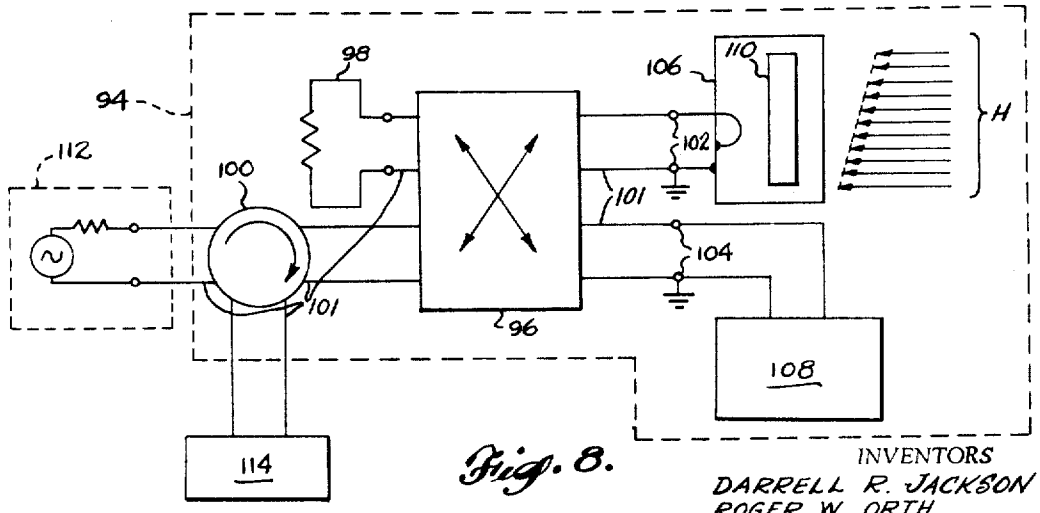


Fig. 8.

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REACTANCE-COMPENSATED PARTICLE-RESONANT, FREQUENCY-SELECTIVE LIMITER

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Fig. 9.

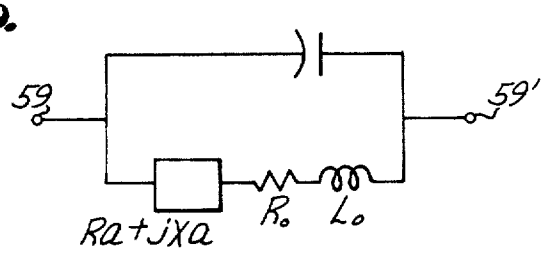


Fig. 10.

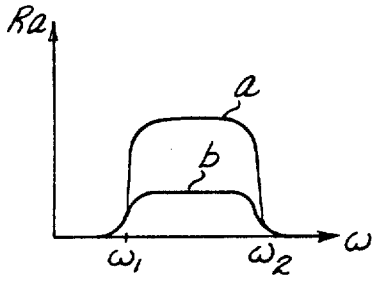


Fig. 11.

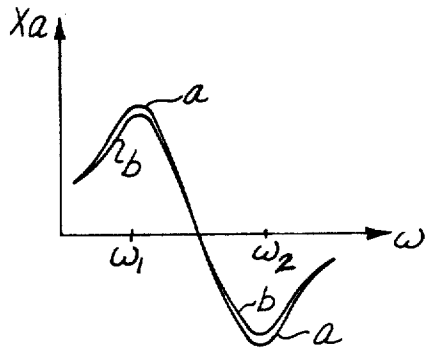


Fig. 12.

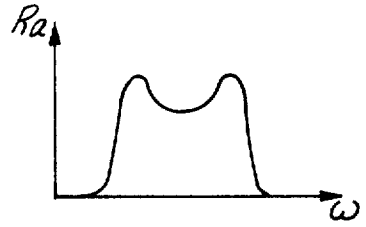
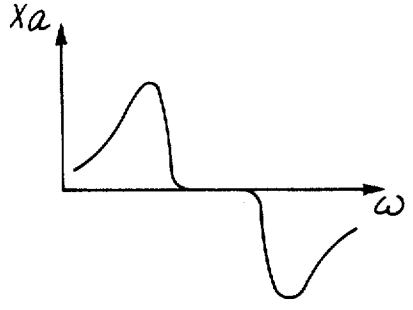


Fig. 13.



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REACTANCE-COMPENSATED PARTICLE-RESONANT, FREQUENCY-SELECTIVE LIMITER

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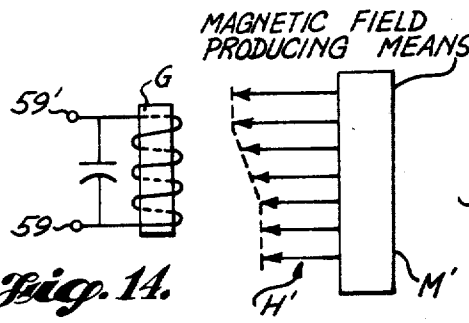


Fig. 14.

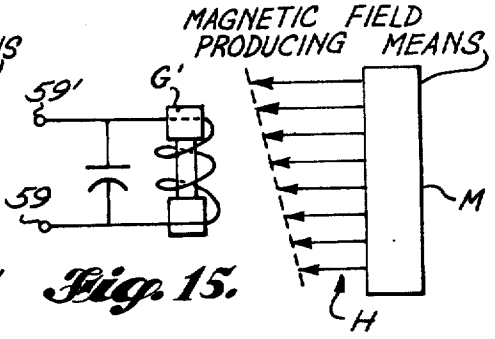


Fig. 15.

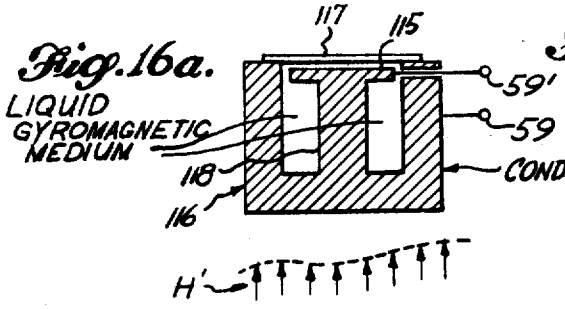


Fig. 16a.

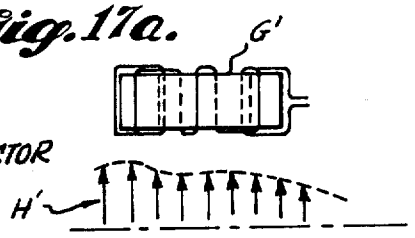


Fig. 17a.

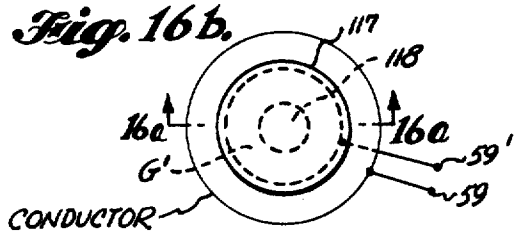


Fig. 16b.

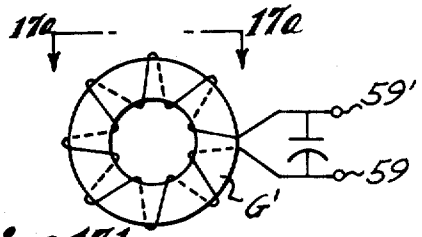


Fig. 17b.

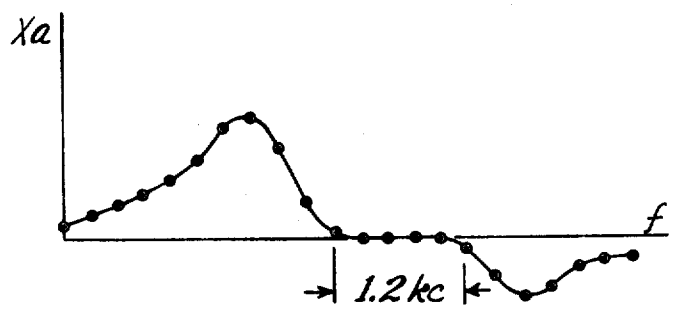


Fig. 18.

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United States Patent Office

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REACTANCE-COMPENSATED PARTICLE-RESONANT, FREQUENCY-SELECTIVE LIMITER

Darrell R. Jackson and Roger W. Orth, Seattle, Wash., assignors to The Boeing Company, Seattle, Wash., a corporation of Delaware

Continuation-in-part of application Ser. No. 357,092, Apr. 3, 1964. This application May 27, 1966, Ser. No. 556,536

8 Claims. (Cl. 324—.5)

ABSTRACT OF THE DISCLOSURE

This invention relates to a frequency-selective limiter using particle resonance effects, and more particularly to a reactance-compensated limiter for use as an anti-interference device. Known frequency-selective limiters of the type which are improved by the present invention generally employ a gyromagnetic resonant material or the like disposed in a magnetic field and coupled with circuitry conditioning the system for resonance of gyromagnetic bodies in the material, and are operable to limit or filter interference signals selectively so as to permit detection of an otherwise masked input signal. The unusual improvement provided herein utilizes a reactance (or dispersion) compensation technique permitting the limiter to have a relatively wider bandwidth, low insertion loss, and a high limiting range.

Cross-reference

This application is a continuation-in-part of pending application Ser. No. 357,092, filed Apr. 3, 1964, in the name of Darrell R. Jackson, and entitled, "Anti-Interference Device."

Background

Frequency-selective limiters generally are described by K. L. Kotzebue in "Frequency-Selective Limiting," I.R.E. Transactions on Microwave Theory and Technique, vol. MTT-10, pp. 516–520, November 1962, and in U.S. Patent No. 3,147,472 to R. H. Varian. Other references will be cited below. The limiting device described by Varian employs a nuclear resonance material and uses crossed coils as a means for coupling into and out of the gyromagnetic system. Varian's concept may be extended to a system employing a bridge circuit [see Gutowsky, "Physical Methods in Chemical Analysis" (Academic Press, New York, 1965), pp. 335, 338–341], and it is in terms of a bridge circuit arrangement that the magnetic resonance limiter is discussed herein.

Either a classical or quantum mechanics approach can be used to explain the phenomenon of gyromagnetic resonance effects. Since thorough discussions can be found elsewhere, a brief discussion is given here based on the quantum mechanics approach. Magnetic resonance involves the absorption of electromagnetic energy by a system of particles such as protons or electrons which are immersed in a D.C. magnetic field. These particles behave as microscopic magnetic dipoles and therefore may be expected to interact with the D.C. field. Quantum mechanics indicates that when the particles are immersed in a magnetic field, each particle dipole moment will be polarized so that one of two values of energy

will be assumed, corresponding to two possible polar orientations. The particle energy is then said to be quantized.

In a typical resonance device an electromagnetic field is established by an inductance element, the energy of which is sought to be absorbed by the particle system placed within the field. The incident electromagnetic wave energy is quantized in units known as photons, and this wave is absorbed only when the photon energy therein is equal to the separation of the two energy levels of the quantized particles. The absorption process takes place in two steps: the excitation of the particle from its lower energy state to a higher state by absorption of an incident photon, and the relaxation of the excited particle back to the lower state where it can absorb another photon. The first step removes an amount of energy from the electromagnetic wave equal to the photon energy. In the second step, the relaxation involves a transfer of energy from the excited particle to the bulk of surrounding material, for example, to the kinetic energy of surrounding molecules. The relaxation time is an average of randomly occurring energy transfers.

Relating the above described phenomenon to the present invention, consider the behavior of the above described system as a function of electromagnetic field strength. At low signal power levels with concomitant low photon density of the electromagnetic waves, excitation of the particles occurs only occasionally. These excited particles will have ample time to return to thermal equilibrium, i.e. the lower energy state, between successive excitations and therefore the entire system will remain at thermal equilibrium. The power absorbed by the system is proportional to the incident power under this condition of equilibrium and the power absorption characteristic of the system is equivalent to a linear resistance. However, if incident power is increased to a level where the mean time between excitations is less than the relaxation time, thermal equilibrium is destroyed and the absorption ability of the system decreases. This decrease results because a large number of particles occupy the higher energy state where photon absorption is impossible. The power level at which photon density produces a rate of excitation equal to or greater than the rate of relaxation, therefore, establishes a saturation power threshold above which an increase in incident power does not produce a proportionate increase in absorbed power.

The saturation effect present in particle magnetic resonance also occurs in other types of resonant systems which satisfy the requirements for an effective anti-interference device. The requirements for a frequency selective limiter are essentially: (1) the resonant material must exhibit a natural narrow linewidth resonance, on the order of at least one-hundred times less in width (measured in cycles) than the frequency at which the resonance occurs; (2) the resonant frequency of the material particles must shift with the application of an external D.C. electric or magnetic field; (3) the resonance of the material must saturate due to disruption of thermal equilibrium at large incident powers; and (4) the substance must be substantially electrically nonconductive. Some of the types of resonant systems which satisfy these requirements are listed as follows: nuclear magnetic, elec-

tron magnetic, nuclear quadrupole, molecular rotational, and molecular inversion. The latter two resonance types may be generally referred to as non-magnetic resonant systems, since the resonant frequency shift necessary for frequency selective limiting is produced by application of a D.C. electric field to the various materials which exhibit these types of resonance.

Another type of shifting means which can be used for example with the nuclear quadrupole resonant system is an internal shifting means. An internal electric field may be produced in a crystalline structure by disruption, such as physical deformation of the structure, which causes a shift in the resonant particle frequencies similar to the shift produced by an external magnetic field. The magnetic resonant systems have been found to be preferable for use in anti-interference devices with which the present invention is concerned. Accordingly, the anti-interference device embodiments described herein are confined to circuits using particle magnetic resonance.

Depending upon the application intended for the anti-interference device, the magnetic resonant material may be chosen to exhibit either nuclear or electron resonance. Since it is desirable to have a narrow natural resonance bandwidth or linewidth, a material exhibiting proton resonance is the most suitable nuclear resonant material. Protons in heavier atoms, on the atomic scale, do not resonate as individual units but rather the nucleus as a whole resonates. This resonance of the entire nucleus is much weaker with respect to absorption and therefore it is preferable that the proton resonant material have hydrogen atoms in its molecular structure wherein the resonating nucleus comprises a single proton. Examples of this type of absorbing material are water, paraffin, ethyl alcohol, glycerin, and mineral oil, all of which have "free" protons. Proton resonance linewidth of water is approximately one cycle per second. This extremely narrow linewidth offers excellent frequency selectivity.

In electron resonance type limiters the materials utilized have electrons whose magnetic dipole moments are not cancelled by the dipole moments of nearby electrons. Although there is a natural tendency for such cancellation in most materials, organic salts containing free radicals such as naphthalene and diphenyl trinitrophenyl hydrazyl or materials with free conduction electrons such as lithium and silicon are excellent electron resonance exhibiting materials. Lithium, for example, when finely divided and in suspension or when dissolved in a suitable solvent, shows a resonance linewidth of approximetaly one-hundred kilocycles. While this linewidth is several orders of magnitude greater than water, a proton resonant material, the electron dipole moment is stronger than in a proton and therefore interacts more strongly with an incident electromagnetic field to provide greater absorption.

It is well known that a frequency selective limiter of the ferrite-type may be used as an anti-interference device by selectively attenuating large interference spectral components while passing small desired components of an input signal. Conventional ferrite limiters, however, provide only partial frequency selectivity because they cannot discriminate between two components unless the components are separated by at least one megacycle. Since most communication systems have bandwidths of no more than a few megacycles, the lack of selectivity inherent in ferrite limiters precludes their use as effective anti-interference devices. The use of particle magnetic resonance can improve the selectivity of such limiters.

It is known that gyromagnetic systems using inhomogeneous D.C. fields behave in a nonlinear fashion (see A. M. Portis, "Electronic Structure of F Centers: Saturation of the Electron Spin Resonance," Physical Review, vol. 73, pp. 1071–1078, September 1953). This nonlinearity is important in that it limits the feasibility of limiters such as that described by Varian, cited above. It will be shown herein that the response of the magnetic resonant material to the driving RF magnetic field in a conventional limiter is nonlinear in such a way that the limiting action is greatest for signals nearest the center of the passband, where the reactance of the system is small, and smallest nearer the extremities of the passband, where the reactance is large, even at large signal levels.

It is found that the essential requirement for overcoming this disadvantage is that the resonant material and the means for producing a nonuniform magnetic field be such with respect to one another that there is a concentration of resonant particles at the end portions of the resonant system. Stated another way, the requirement is that absorption maxima be formed near the edges of the passband, resulting in reactance compensation over an extended region in the central portion of the passband.

The principal object of the invention is, therefore, to provide a reactance compensated frequency-selective limiter. This object is fulfilled in some embodiments of the invention by provision of special geometric configurations for the gyromagnetic material itself and/or the magnetic field in which it is inserted in order to achieve the required resistance (absorption) and reactance characteristics.

With this background and the more specific description which follows below the present invention will be understood to provide a system which permits selective attenuation of interfering signals that lie within a relatively wide bandwidth of some desired signal spectrum. An anti-interference device according to this invention can be made simple and compact in design, and makes possible the reception of signals which would otherwise be lost in interference. Prior attempts to achieve these objects have resulted in devices that are either too bulky and complex to be of use in airborne systems, for example, or they distort the desired signal excessively. The present device is basically a two-terminal adaptable impedance functioning as a frequency selective limiter, matched filter, comb filter, or the like, which, when inserted in a suitable network, provides selective filtering action.

These and other features, objects and advantages will become more apparent from the following description of preferred forms of the invention depicted in the accompanying drawings.

Description

FIGURE 1 is a graph showing the power input to an ordinary limiter.

FIGURE 2 is a graph showing the power output of an ordinary limiter.

FIGURE 3 is a graph showing the power input to an "ideal" frequency-selective limiter.

FIGURE 4 is a graph showing the power output of an "ideal" frequency-selective limiter.

FIGURE 5 is an anti-interference device using magnetic particle resonance.

FIGURE 6 is a modified anti-interference device using magnetic particle resonance and incorporating a shaped magnetic field according to the invention.

FIGURE 7 is another modified anti-interference device using magnetic particle resonance.

FIGURE 8 is an anti-interference device for microwave applications using magnetic particle resonance.

FIGURE 9 is an equivalent circuit for a portion of the device shown in FIGURE 6.

FIGURES 10 and 11 are diagrams illustrating the resistance and reactance characteristics, respectively, of the circuit of FIGURE 9 in response to a single signal of frequency ω.

FIGURES 12 and 13 are diagrams illustrating the resistance and reactance characteristics when the compensation technique of the invention is employed.

FIGURES 14 and 15 diagrammatically illustrate em-

bodiments of the invention wherein, the magnetic field and the gyromagnetic material are specially formed, respectively, to achieve the desired result.

FIGURES 16*a*, 16*b* and 17*a*, 17*b* diagrammatically illustrate additional configurations of magnetic field and gyromagnetic material according to the invention.

FIGURE 18 is a typical spin reactance characteristic curve obtained experimentally by use of the invention.

Referring now to FIGURES 1 through 4, a comparison of the effectiveness of two types of anti-interference devices are shown. FIGURES 1 and 2 show the attenuation characteristics of a conventional frequency selective limiter. The combined power spectrum input of weak desired spectral components and strong interfering components is shown in FIGURE 1 as applied to a conventional limiter; FIGURE 2 shows the output of the limiter. While attenuation of the interfering components has been effected, severe cross-modulation between the desired frequency components and the interference frequency components has taken place. In FIGURE 3, the input to an "ideal" frequency selective limiter is shown with the corresponding output shown in FIGURE 4. It is apparent from the output shown in the latter figure that the signal-to-interference ratio is considerably improved without any serious cross-modulation. Moreover, any increase in the input power of the interference components would not affect the output. The "ideal" limiter also becomes increasingly more effective when interfering signal power becomes more coherent, since a coherent signal is concentrated in fewer spectral components of larger magnitude rather than distributed in lesser components which may be smaller than the desired signal power. The frequency selective limiter of the present invention approaches the "ideal" limiter shown in FIGURES 3 and 4 and provides wider bandwidth capabilities than previous particle-resonance limiters of this type.

In connection with FIGURES 5 to 8 different configurations of circuitry will now be described, any of which can be employed in practicing the invention.

Referring to FIGURE 5, one form of anti-interference device using nuclear magnetic resonance includes a simple Wheatstone bridge circuit having four arms **10**, **12**, **14** and **16**. Arm **16** has a resistive member **18** and a parallel resonant L-C circuit **20** in parallel with the resistance **18**. The L-C circuit **20** has a capactive member **22** and an inductive member **24**. A particle-resonant material **26** is immersed within the A.C. field established by the inductive member **24**. A means for shifting the natural frequencies of the particles in material **26** is provided to produce a particle-resonant frequency range which is equal to the range or width of the anti-interference device bandwidth. The resonant material **26** exhibits proton magnetic resonance. The means for shifting the particle frequencies comprises means M for producing a magnetic field H which in this case varies linearly along the material **26**. Means M, comprises a D.C. electromagnet essentially perpendicular to the axis of inductive member **24**. The arm **14** of the bridge has an impedance member **28** which will balance the impedance of arm **16** when the resonant material **26** is saturated.

In operation, a signal is introduced through input circuit means **30** electrically coupled to the bridge circuit. If the signal power level is small, thermal equilibrium of the particles in the resonant material **26** is sustained and the circuit **20** impedance, in parallel with the impedance of member **18**, results in an imbalance between arms **16–14** and arms **10–12** so that a signal appears at output circuit means **32**. The impedance of circuit **20** remains constant as signal power is increased and the output power is a linear function of the input power. When the signal power is increased sufficiently so as to saturate material **26**, i.e. exceed the power threshold value, the impedance of the circuit **20** increases so as to balance the bridge and limit signal output. The effect of this circuit is to provide a frequency-selective limiter for a limited bandwidth wherein a multiplicity of particles function like individual narrow-band filters with good selectivity because of the narrowness of the bandwidth of each "particle-filter." Its bandwidth capabilities can be improved according to the invention as is hereinafter explained.

Referring to FIGURE 6, a second and more practical form of anti-interference device using nuclear magnetic resonance is shown. This particular circuit is designed for radio frequencies and is basically a bridge circuit means having two arms **34** and **36** having parallel resonant circuit means **38** and **40**, respectively. The circuit **40** has a variable capacitor **42** and an inductance **44**, and is balanced with the circuit **38** comprising a variable capacitor **46** and an inductance **48**, the latter containing a proton resonance material **50** disposed within its A.C. field. The resonant material **50** is immersed in a polarizing magnetic field H generated by means M' and in this case having a special configuration according to the invention as hereinafter discussed. The field is oriented at approximately 90° to the inductance coil **48** axis. The signal input circuit means **52** comprising transformer **54** provides the input signal to the bridge circuit. An output means **58** is connected between a center tap **56** on transformer **54** and the junction between arms **34** and **36**. Nuclear resonance absorption of the input signal by the material **50**, in the manner previously explained, will unbalance the bridge so that a signal appears at the output terminals. At large input signal power levels, the nuclear resonant material **50** is saturated exceeding a threshold value, causing the bridge to rebalance, limiting the output signal power, and thereby attenuating the interference frequency spectral component.

In FIGURE 7 the bridge circuit means has two arms **60** and **62** comprising series resonant circuit means **64** and **66**, respectively. The circuit means **64** comprises a variable capacitance **68**, a variable resistance **70**, and an inductance **72**. The circuit means **66** comprises a variable capacitance **74**, a variable resistance **76** and an inductance **78**. The inductances **72** and **78** comprise the secondary of a transformer **80**, the transformer serving to inductively couple the signal source **82** to the bridge circuit. An output load **86** is connected to a center tap **84** which electrically divides the transformer secondary into the two inductances **72** and **78**. The inductive coil **72** has disposed within its A.C. field a proton resonance material **88** which is also immersed in a nonuniform magnetic field H arranged at 90° to the field established by inductance **72**. Special circuit means **90** magnetically coupled to the system through coil **92** is employed as will be described to improve the circuit operation in accordance with the invention.

In the systems described above, the output signal can be separated into two components: an in-phase or absorption component produced by power dissipation in the particle resonance material, and a quadrature or dispersion component caused by reactive energy storage in the material. Saturation of the former component occurs at relatively moderate power levels, though above the thermal equilibrium level, but saturation of the quadrature component occurs only at extremely high power levels. This effect is detrimental to the operation of the frequency selective limiter since the presence of quadrature nonsaturation results in large signals leaking through the limiter without attenuation. To prevent this degradation of the limiter effectiveness, a quadrature compensation means is used according to the invention, as will now be explained.

As previously described, the device shown in FIGURE 6 includes a bridge circuit suitable for use in a gyromagnetic limiter. The resonant L-C circuit connected between terminals **59** and **59'** can be replaced by the equivalent circuit shown in FIGURE 9 wherein L_o represents the ordinary self-inductance of the coil in the absence of magnetic resonance, R_o represents the ordinary series resistance of the coil, R_a represents the change in resistance

of the coil due to magnetic resonance, X_a represents the change in reactance due to magnetic resonance, and j is equal to $\sqrt{-1}$. The quantities R_a and X_a will depend upon frequency and RF magnetic field strength H_1. The fact that R_a and X_a depend upon H_1 indicates that the response of the magnetic resonance material to the driving RF field is nonlinear. This nonlinearity is important for it gives rise to the limiting phenomenon of prior frequency selective limiters such as described by Varian.

FIGURES 10 and 11 serve to illustrate this nonlinear behavior in terms of the quantities R_a and X_a. These curves, respectively, give the values of R_a and X_a for excitation by a single signal having frequency ω.

As is well known, the gyromagnetic bodies in a resonant material placed in a magnetic field H precess at a characteristic angular frequency called the Larmor frequency, which is proportional to the intensity of the applied field. In prior systems inhomogeneous fields varying linearly along the material length have been utilized so that the Larmor frequencies of the individual gyromagnetic bodies (nuclei or electrons) are distributed more or less uniformly over the frequency range given by $\omega_1<\omega<\omega_2$. The curves labeled *a* hold for "small" nonsaturating signals only, while the curves labeled *b* hold for a "large" saturating signal of some particular magnitude. It is evident from FIGURES 10 and 11 that R_a diminished markedly at large signal levels while X_a remains practically undiminished. Referring back to FIGURE 9, it is now possible to predict the behavior of the limiter circuit as a function of signal strength and signal frequency.

Remembering that the bridge circuit of FIGURE 5, for example, is symmetrical except for the inclusion of a gyromagnetic material in one arm, it can be seen that the bridge circuit will be balanced except at frequencies near the Larmor frequencies of the gyromagnetic medium. The diminution of R_a at large signal levels tends to balance the bridge circuit, and consequently tends to limit the power delivered to the load. Limiting action will be greatest for signals near the center of the passband, where X_a is small. At frequencies removed from the band at center, a lesser degree of limiting will occur, since X_a will have an appreciable magnitude even at large signal levels. This property, characteristic of prior frequency-selective limiters, severely curtails their usefulness. For example, the usefulness of one prior art frequency selective limiter was found to be restricted to frequencies in only about the central ten percent of the band between ω_1 and ω_2 in that it was only in this region that 20 to 30 decibels of limiting (large signal suppression) could be obtained. Thus, it may be said that a large percentage of the potential bandwidth is wasted in such prior limiters.

The technique of this invention which greatly improves the characteristics of gyromagnetic limiters involves reducing the magnitude of the reactance or quadrature component caused by reactive energy storage in the material within the central region of the frequency bandwidth.

It is found that the in-phase and quadrature components of the output signal are a function of the geometry of the polarizing field H and/or the geometry of the absorbing materials. Thus according to two forms of the invention special magnetic field configurations or special geometric configurations of the gyromagnetic material, or both, are utilized to achieve resistance and reactance characteristics similar to those illustrated in FIGURES 12 and 13, respectively. The two essential characteristics to be observed from these figures are that the resistance, or absorption, possesses maxima near the band extremities, and the reactance, or dispersion, is very small over an extended region in the central portion of the band.

These two characteristics are not actually independent. according to a well-known theorem (see A. Abragam, The Principles of Nuclear Magnetism (Oxford: Clarendon Press, 1961)) once the small signal absorption characteristic is known, the small signal dispersion characteristics can be determined to within an additive constant. Thus, it may be said that the essential requirement for reactance compensation is the presence of absorption maxima near the passband extremities.

Different embodiments by means of which reactance compensation may be achieved according to the invention are illustrated in FIGURES 6, 7 and 14 to 17*b*. In the forms shown in FIGURES 6 and 14, very similarly shaped D.C. fields are employed to achieve the compensation required. In each case the field gradient is largest for intermediate field values, corresponding to the central portion of the limiter bandwidth, while the gradient is less at the largest and smallest field values, corresponding to the edges of the limiter bandwidth. In FIGURE 6 the field varies according to a smooth curve, while in FIGURE 14 a broken line variation is shown. With either of these arrangements, there is a concentration of gyromagnetic bodies resonant at frequencies corresponding to the bandwidth extremities. This causes an absorption, or resistance, characteristic of the type shown in FIGURE 12 and consequently leads to reactance compensation resulting in a reactance characteristic such as is shown in FIGURE 13.

This same result can be obtained with a more or less uniform D.C. field gradient, by shaping the gyromagnetic medium G as shown in FIGURE 15. As was the case in FIGURE 14, the circuit comprising the gyromagnetic material, the field coil enclosing it, and the capacitance connected across the coil, can be substituted between terminals **59** and **59'** in either the circuit of FIGURE 5 or that of FIGURE 6. Proper shaping can be arrived at experimentally, or by analytical methods using the known properties of such resonant systems in order to produce concentrations of resonant particles (per unit of frequency) in the end regions of the frequency band.

Still another embodiment is shown in FIGURES 16*a* and 16*b* wherein a circular coaxial re-entrant cavity device **116** is shown, which is operated in a TEM mode and filled with a gyromagnetic medium, such as mineral oil or kerosene. Capacitance exists between disc **115** and covering disc **117**. In this case, the presence of the cavity center conductor **118** serves to reduce the amount of absorption in the central region of the bandwidth. In a limiter where the nuclear (or electron) resonance linewidth is much less than the total Larmor frequency bandwidth, it can be shown that X_a actually approaches zero for frequencies in the range corresponding to the spatial region occupied by the cavity center conductor.

If the strength of the D.C. field varies linearly across the cavity, it is found that each cylindrical shell of magnetic resonant particles contributes no reactance at frequencies equal to the Larmor frequencies corresponding to the magnetic fields around the shell. In practice, X_a is not identically zero over this frequency range, but will be small enough to yield excellent limiting characteristics.

If the strength of the D.C. field does not vary linearly across the cavity, but instead varies in some arbitrary (and perhaps unknown) manner, reactance compensation may still occur. It has been shown theoretically, and demonstrated experimentally, that a resonator with circular symmetry, containing gyromagnetic material, will have X_a very small over a definite frequency range for a very wide variety of D.C. field patterns. The principal constraint that must be placed on the D.C. magnetic field is that it must not vary in a too extreme or convoluted manner across the resonator. The conclusion to be reached from the above is that reactance compensation can be achieved for a wide variety of D.C. field patterns, if a circularly symmetric resonator is used. This property is very important, since it greatly simplifies the problem of obtaining a D.C. field with the correct spatial variation. Circular symmetry of the resonator and gyromagnetic material can be attained in a number of ways, of which the embodiment shown in FIGURES 16*a* and

16*b* is only an example. Still another example wherein special geometry is used in both the formation of the A.C. field and in the gyromagnetic material itself is shown in the toroidal coil configuration shown in FIGURES 17*a* and 17*b*.

With the type of compensated limiter just described it has been found possible to obtain 20 to 30 decibels of limiting over a 1.2 kHz. band width, whereas a comparable uncompensated limiter would provide this degree of limiting over a band width on the order of only 200 Hz. The measured reactance characteristic for the limiter built and tested is shown in FIGURE 18.

In the device shown in FIGURE 7 reactance circuit means **90** is employed to produce a quadrature imbalance voltage which compensates the resonance quadrature voltage by adding to the circuit a reactance component which within a predetermined range has a characteristic of approximately equal magnitude and opposite sign from that of the gyromagnetic material within that range. The reactance circuit means **90** may comprise coils, capacitors, resonant cavities, piezoelectric crystals, or magnetorestrictive elements, depending on the resonant system used in the device. Standard techniques of circuit synthesis will determine the elements necessary to provide the required compensating reactance. The reactance means **90** is introduced into the bridge circuit by means of magnetic coupling through a coil **92**. It is to be understood, however, that the proper reactance means could be otherwise coupled to the bridge circuit. Moreover, the means for providing the compensating reactance is independent of the remainder of the circuit means used in the anti-interference device.

Referring now to FIGURE 8, an anti-interference device for microwave application is shown. While any of the various resonant type systems may be used, the limiter shown uses magnetic particle resonance. Microwave bridge circuit means **94** comprises a 3 db hydrid **96**, a matched load **98** and a circulator **100** electrically connected by wave-guides **101** (or coaxial lines or striplines) which can be balanced over a range of frequencies as broad as the bandwidth of the limiter. Connected to the waveguide terminals **102** and **104** of the bridge circuit means **94** are a resonant cavity **106** and a balancing circuit means **108**, respectively. The cavity **106** contains electron resonance material **110**. If this absorbing material does not fill the cavity completely, it should be located in the region of the strong RF magnetic field within the cavity. Either the material **110** or the external D.C. field H, or both, may be shaped as previously described so as to provide the required compensating distribution of particle resonant frequencies. The balancing circuit **108** is designed, by standard techniques, so as to have an impedance which is equal to the cavity impedance when the material **110** is fully saturated. In operation, input signals are introduced into the microwave bridge circuit means **94** through input circuit means **112** through the waveguide **101**. If the signal power level is above the threshold or saturation level of the material **110**, the impedance of the cavity **106** will balance the impedance of circuit means **108**, and a limited signal will appear at output means **114**. However, at signal power levels below saturation, the bridge means **94** is unbalanced and a signal will appear at the load **114**. The frequency-selective limiter action is thereby effected.

While there has been shown and described the fundamental novel features of this invention as applied to the various preferred embodiments, it will be understood that omissions, substitutions and changes in form and details of the anti-interference devices illustrated may be made by those skilled in the art without departing from the scope of the invention. It is the intention therefore to be limited only by the scope of the following claims and reasonable equivalents thereof.

What is claimed is:

1. A particle-resonance limiter:

(a) a resonant system including,

(1) resonant material having natural narrow linewidth resonance particles saturable by signal components above a threshold power level so as to cause a change in impedance of said material, said resonant material being substantially electrically nonconductive, and

(2) field producing means for distributing the natural frequencies of the particles in said resonant material to produce a predetermined particle frequency range;

(b) bridge circuit means having one or more pairs of arms including,

(1) a first arm comprising resonant circuit means including said resonant system, and

(2) a second arm comprising circuit means for balancing said bridge circuit means when said resonant material is saturated,

(c) input circuit means coupled to apply an input signal to said bridge circuit means; and

(d) output circuit means coupled to said bridge circuit means for providing a frequency selective limited signal to a load when said first pair of arms are impedance unbalanced;

(e) said resonant material and said field producing means being formed with respect to one another such that there are greater numbers of said particles resonant at the end portions of said frequency range than at the center portion thereof.

2. The limiter defined in claim **1** wherein said resonant material particles are protons and said field producing means comprises means for producing a nonuniform magnetic field in which said protons are immersed.

3. A particle-resonant frequency-selective limiter comprising

(a) a resonant system including substantially electrically nonconductive material having natural narrow bandwidth resonance particles saturable by signal components above a threshold power level so as to cause a change in impedance of said material, and means for producing a field in which said material is immersed, said material and field being formed relative to one another whereby the resonance frequencies of the particles in said material are distributed over a predetermined frequency range;

(b) circuit means coupled to said material and including input means operable to apply an input signal to said material, and output means operable to derive from said material an output signal having an in-phase component produced by power dissipation in the material and a quadrature component caused by reactive energy storage in the material, said in-phase component being substantially limited by saturation in said material at those frequencies at which the input signal power exceeds said threshold power level; and

(c) compensation means operatively coupled with said resonant system and circuit means and operable to render said quadrature componnet substantially zero within a substantial portion of said frequency range.

4. The limiter defined in claim **3** wherein said compensation means comprises a reactance circuit adding to said circuit means a reactance component having a characteristic of substantially equal magnitude and opposite sign from the reactance characteristic of said limiter without said compensation means, within said portion of said predetermined frequency range.

5. The device defined in claim **3** wherein said compensation means comprises means in said field producing means for establishing a field intensity distribution varying along said resonant material such that the field gradient is substantially zero at the extremities thereof and changes through a maximum along the material between said extremities.

6. The device defined in claim **3** wherein said com-

pensation means comprises a predetermined configuration of said resonant materal wth respect to sad field whereby there are concentrations of resonant particles in portions of said material spaced within said field, thereby establishing peaks near the end portions of the absorption characteristic of said limiter.

7. The device defined in claim 6 wherein said resonant material has an annular configuration having its axis oriented substantially parallel to the direction of said field, and wherein said field varies in intensity in a direction perpendicular to said axis.

8. The device defined in claim 7 further including means for confining said material, said confining means

comprising an electrically conductive element of coaxial shape coupled in said circuit means and having a reentrant cavity in which said material is confined.

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