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Mergerian

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[54] CYCLOTRON RESONANCE FREQUENCY-SELECTIVE LIMITER USING INHOMOGENEOUS RF MAGNETIC FIELD

[72] Inventor: **Dickron Mergerian**, Baltimore, Md.

[73] Assignee: **Westinghouse Electric Corporation**, Pittsburgh, Pa.

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[52] **U.S. Cl.**.....**325/473**, 313/62, 328/165, 328/167, 328/234, 333/24.1, 325/332, 325/377, 325/387, 325/479

[51] **Int. Cl.**.....**H04b 1/10**

[58] **Field of Search**.....325/473, 477, 490, 105, 332, 325/347, 451, 377, 386–388, 436, 482, 479; 333/24.2, 24.1; 307/237, 308–310; 330/4.8, 5; 313/62; 328/165, 167, 234

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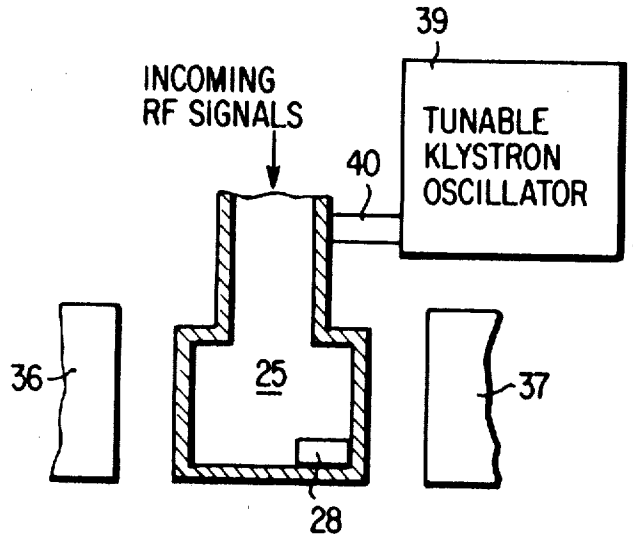
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Primary Examiner—Robert L. Richardson
Assistant Examiner—Albert J. Mayer
Attorney—F. H. Henson and E. P. Klipfel

[57] **ABSTRACT**

A tunable limiter is disclosed which utilizes a semiconductor containing an excess of free electrons and having a cyclotron resonance line which is inhomogeneously broadened. The semiconductor is exposed to a static magnetic field and spatially inhomogeous RF electric field at the cyclotron resonance frequency, within a waveguide cavity. The RF electric field is derived from the incoming signal, which contains information as well as possible jamming signals. By virtue of the thermo-electric-cyclotron-resonance effect, power from signals exceeding a saturation level set by the intensity of the RF field causes saturation of the limiter, but only at the frequency of those signals. This provides limiting of intense jamming signals without disturbing information signals at nearby frequencies.

10 Claims, 4 Drawing Figures



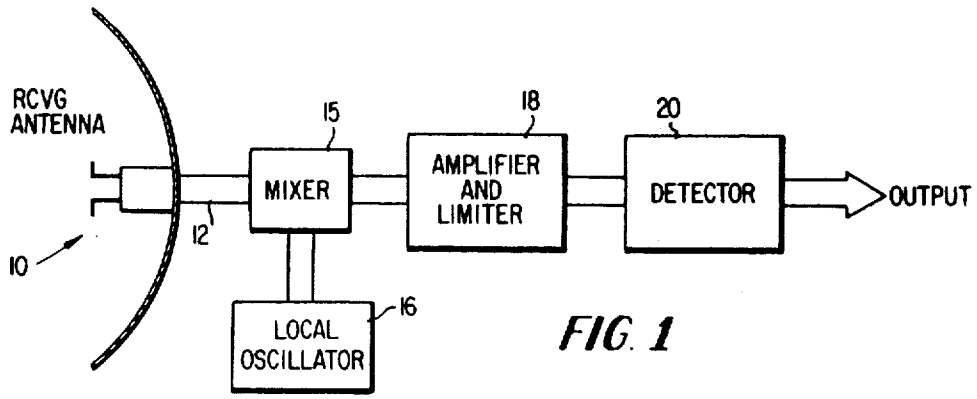


FIG. 1

FIG. 2

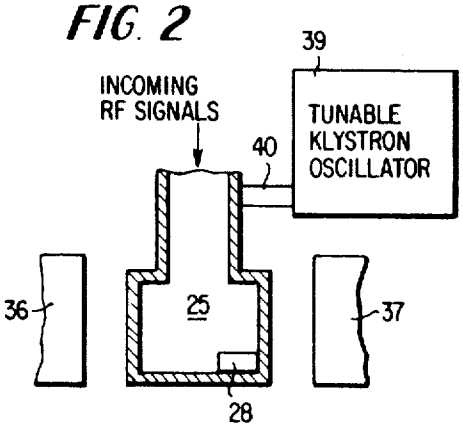
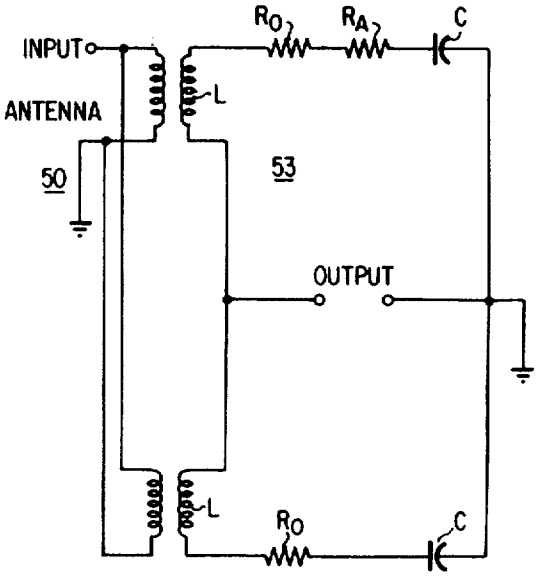


FIG. 3



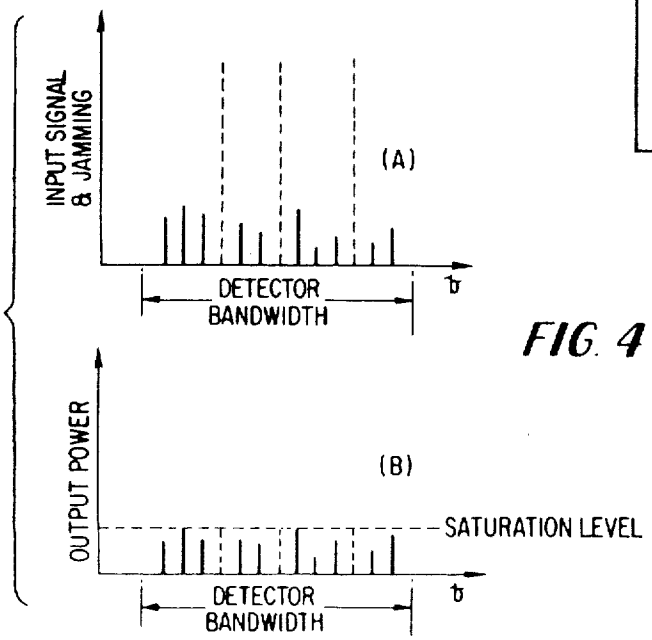


FIG. 4

CYCLOTRON RESONANCE FREQUENCY-SELECTIVE LIMITER USING INHOMOGENEOUS RF MAGNETIC FIELD

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed toward a tunable microwave limiter, and is particularly concerned with a limiter adapted for use in an RF receiver, to preclude jamming of a detector of wide bandwidth in the receiver.

2. Prior Art

The jamming of radio receiving equipment by hostile forces is a constant threat to any military and defense effort. Such disruption of reception of intelligence is generally accomplished by interfering signals emitted from a hostile transmitter in the form of intense narrow band bursts of microwave power. The interfering signals are usually distributed over a rather wide region of the frequency spectrum to completely saturate the broadband detector in a receiver designed to operate within that frequency band and within the signal range. It is, of course, desirable to provide means to avoid such jamming so that the detector will continue to function regardless of the presence of one or more high power jamming signals within the bandwidth of the detector. However, the proposed methods of eliminating jamming have not achieved any great degree of success in the past.

SUMMARY OF THE INVENTION

Before describing the present invention, it will be useful to discuss the phenomenon on which the invention is based, and from which it derives its anti-jamming capabilities. It is well known that when an electron temperature gradient exists across a semiconductor sample, it is accompanied by a voltage across the sample. This is commonly referred to as the thermoelectric effect, or Seebeck effect. Such an electron temperature gradient may be produced by the interaction of electromagnetic radiation with charge carriers in solids, and in fact, cyclotron resonance in semiconductors may be observed as a thermoelectric voltage induced by cyclotron heating of the free carriers in the semiconductor in a spatially inhomogeneous microwave electric field. This so called Thermo-Electric-Cyclotron-Resonance (TECR) effect (see, e.g., P. D. Fisher and P. E. Wagner, "Thermoelectric Cyclotron Resonance in Semiconductors," Applied Physics Letters 9 153 (1966), may be described briefly as follows.

If a semiconductor sample is placed in a crossed static magnetic field H and an RF electric field of magnitude E_{RF} and frequency $\nu=(eH/2\pi m^*c)$, where m^* is the effective mass of one of the charge carriers in the semiconductor, e is the charge on a carrier (an electron), and c is the speed of light, then microwave power is preferentially absorbed from the RF field by carriers of mass m^*. Adjustment of the frequency

$$\left(\upsilon=\frac{\omega}{2\pi}\right)$$

of the external radiation such that

$$\upsilon_\tau=\frac{eH_\tau}{2\pi m^*c}$$

where τ is the carrier collision time, is the condition for cyclotron resonance. The average energy transferred to the charge carriers (i.e., to the free electrons in the semiconductor) is proportional to the square of the RF electric field magnitude, assuming that the collision time is independent of energy. The theory of equipartition of energy relates this increase in energy of the carriers absorbed from the field to an increase in carrier temperature, namely, $\Delta T_{CR} \alpha E_{RF}^2$, where ΔT_{CR} is the change in the effective temperature of the charge carrier of mass m^*. If E_{RF} possesses a spatial gradient across the semiconductor sample, then, a gradient will also exist in the effective temperature of charge carriers of mass m^* across the sample, and it is this ΔT, or temperature gradient, which gives to a "thermo-electric" voltage.

Thus, in brief, the TECR effect manifests itself as the establishment of a voltage across a semiconductor sample, as a consequence of preferential absorption of microwave radiation by charge carriers in a given spatial region of the sample and the resultant cyclotron heating of these carriers, when the semiconductor sample is simultaneously subjected to a static magnetic field and a spatially inhomogeneous microwave electric field at the cyclotron resonance frequency.

Briefly, according to the present invention, advantage is taken of the TECR effect to provide an anti-jamming device in the form of a microwave limiter, based upon the fact that the cyclotron resonance line is inhomogeneously rather than homogeneously broadened. This fact is experimentally verified, as reported, for example, by P. D. Fisher in "Thermo-Electric-Cyclotron-Resonance in Semiconductors," Technical Report AFAL-TR-67-19, The John Hopkins University, Carlyle Barton Laboratory, March 1967. As a consequence of the inhomogeneous broadening, microwave energy incident on the semiconductor sample within the overall cyclotron resonance linewidth is absorbed selectively at one portion of the line and saturates that portion only. The remainder of the resonance line is unaffected. In contrast, homogeneous broadening would result in uniform absorption of microwave power over the entire resonance line, leading to uniform overall line saturation.

The inhomogeneous broadening of the resonance line exhibited by the TECR effect can be utilized to achieve selective absorption of radiation over a narrow band which falls within the overall bandwidth of an RF receiver. Moreover, this overall bandwidth can be controlled by merely altering the electron collision time of the semiconductor sample (e.g., by temperature control). Hence, the overall bandwidth may be selected to be as broad as desired without the threat of jamming, because any narrow band intense jamming signal detected by the receiver is absorbed over a correspondingly narrow band by a limiter utilizing the TECR phenomenon. Absent such a limiter, the narrow band jamming signal would saturate the detector in the receiver, with a consequent loss of intelligence during the period of saturation. With the limiter, however, only the narrow frequency band occupied by the jamming signal is saturated, so that the remaining signal information in the overall band passes unaltered to the detector. The center frequency of the bandwidth of the limiter is tunable by simply varying the amplitude of the static magnetic field.

It is therefore a principal object of the present invention to provide a tunable microwave limiter capable of selective absorption of microwave radiation in one or more narrow bands within the overall bandwidth of the limiter.

Another object of the invention is to provide a limiter for an RF receiver, in which the limiter relies on thermo-electric-cyclotron-resonance effect to prevent wideband jamming of the receiver.

Still another object of the invention resides in the provision of a limiter which includes semiconductor material containing free electrons exposed simultaneously to a static magnetic field and a spatially inhomogeneous electric field at the cyclotron resonance frequency, to effect preferential transfer of energy from RF signal incident on the limiter at selected narrow bands within a relatively wide overall band.

BRIEF DESCRIPTION OF THE DRAWINGS

In describing the invention, reference will be made to the accompanying drawings, in which:

FIG. 1 is a simplified block diagram of the front end of a typical receiver system;

FIG. 2 is a simplified fragmentary diagram, partly in section, of an embodiment of a limiter for use in the receiver of FIG. 1;

FIG. 3 is a schematic diagram of an equivalent circuit for a portion of the receiver including the limiter; and

FIG. 4A and 4B are graphs useful in explaining the operation of the limiter.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Before describing the invention, reference is made to FIG. 1, showing a simplified diagram of a typical receiver. Microwave signals which include information-bearing signals and which may also include jamming signals are incident on and are absorbed by a receiving antenna **10**. The signals are thereupon supplied via a feedline **12** to a mixer **15** which also receives an input from a local oscillator **16**. The output of the mixer is applied via a waveguide, for example, to an amplifier and limiter **18** which supplies signal to a detector **20**. The output of the detector is further processed as required to obtain the information carried by the incoming signals. In an ordinary receiver of the prior art type, the presence of an intense jamming signal anywhere in the detector bandwidth is sufficient to produce jamming of signals throughout the band.

According to the present invention, the receiver utilizes a limiter of the type shown in FIG. **2**, to prevent such overall jamming. Referring to FIG. **2**, a waveguide cavity **25** is formed from a section of waveguide along which the incoming signal passes. The incoming signal is designated by the general label "RF" to signify that it is in a portion of the RF spectrum, although obviously it may constitute IF signal. A slab **28** of semiconductor material, hereinafter sometimes referred to as a semiconductor sample, is positioned within the cavity. Obviously, the microwave cavity **25** may simply be a section of waveguide which has been shorted electrically by appropriate use of an end wall of conductive material. If the cavity **25** is of rectangular cross section, as is intended to be shown in FIG. **2**, then the slab **28** should be positioned close to a boundary surface, i.e., a wall of the cavity, since that location is the region in which the maximum field strength will appear. In any event, for any given cavity, the semiconductor sample should be placed in the position of maximum spatial inhomogeneity of the electric field derived from the incoming RF signal.

The semiconductor sample **28** is also subjected to a static magnetic field, which may be established by any suitable means outside the microwave cavity **25** itself, but in such a manner to insure that the field extends into the cavity and that sample **28** is subjected thereto. In the exemplary embodiment of FIG. **2**, this field is established by a pair of pole pieces **36** and **37** of opposite polarity external to the cavity. The center frequency of the band over which the limiter is effective may be tuned by simply altering the magnitude of the static magnetic field in any conventional manner. Moreover, the overall bandwidth of the limiter of FIG. **2** may be varied by appropriate variation of the collision time of free electrons within semiconductor sample **28**. This is readily achieved by regulation of the temperature of the medium in which the cavity **25** is immersed.

The semiconductor material of which slab **28** is composed should be *n*-type to insure an abundance of free electrons which are to undergo cyclotron resonance. For example, *n*-type germanium (Ge) is suitable for use as the semiconductor material at liquid helium temperatures, whereas indium antimonide (InSb) is suitable as the semiconductor material for use at higher temperatures. However, the only critical aspect in selection of the particular semiconductor material is that it have a cyclotron resonance linewidth that is inhomogeneously broadened. Preferably, the semiconductor material is doped to provide from approximately 10^{17} to 10^{18} free electrons per cubic centimeter, regardless of the specific semiconductor material employed. For germanium, a resistivity of 10^{-8} ohm-centimeter is desirable, whereas for indium antimonide a resisitivity of 10^{-2} ohm-centimeter is desirable. The static magnetic field to which the semiconductor material is subjected is preferably a magnitude on the order of about 3,000 Gauss. This static magnetic field may be homogeneous or inhomogeneous, although the degree of isolation to be achieved by the limiter is variable according to the inhomogeneity of the magnetic field.

The microwave RF field to which the semiconductor slab **28** is subjected to achieve the anti-jamming characteristics of the limiter is obtained from the received signals. In particular, microwave signals at the cyclotron resonance frequency are picked up by the receiving antenna. These signals supply an input to the limiter by way of cavity **25**, thereby producing an RF electric field, which is superimposed on the static magnetic field in the cavity.

This RF field is spatially inhomogeneous in that a different field strength is present at different portions of the slab, the character of the field being inherent as a consequence of the waveguide environment. The cyclotron resonance line is inhomogeneously broadened so that energy from the incoming RF signal picked up at the receiver is absorbed selectively by slab **28** over narrow band portions of the resonance line corresponding to the specific frequencies of the signals. Accordingly, any intense narrow band jamming signals picked up at the antenna and exceeding a preselected saturation level are absorbed in the limiter at only their respective narrow bands within the overall bandwidth of the receiver. The saturation level may be established in part by the output of a tunable klystron oscillator **39** (FIG. **2**), and is preselected in further part by other parameters which will be discussed presently. The output of klystron oscillator **39** is set, depending upon these other parameters and upon the expected level of the desired incoming signal, to designate a level which, if exceeded by any incoming signal, will produce saturation. It is to be emphasized, however, that a saturation level will be established merely on the basis of the concentration of free charge carriers and the collision cross section of the free charge carriers in the semiconductor sample **28**, so that an oscillator such as **39** need not be utilized at all, unless somewhat more precise level control is desired. In any event, only those information-bearing signals in the exact narrow band of the jamming signals that exceed this saturation level will be affected by the jamming. If homogeneous broadening of the cyclotron resonance line were permitted, the jamming signals would be effective to interfere with all information-bearing signals throughout the detector bandwidth, regardless of the extreme narrow band character of the jamming signals.

Referring to FIG. **4A**, the information bearing signal which is desired to be recovered is represented by the solid lines within the detector bandwidth. Jamming signal is represented by dotted lines at relatively few points (i.e., at narrow bands) within the detector bandwidth. The jamming signal is typically of much greater intensity than the information signal level since the jamming signal is usually simply a burst of power occupying a very narrow band. This substantially greater magnitude of jamming signal is represented by the much greater height of the dotted lines than the solid lines in FIG. **4A**. The output power of the limiter relative to the detector bandwidth is indicated in FIG. **4B**. The jamming signal is effective only at the corresponding narrow bands in which it appears, being clipped at a substantially lower level signified by the saturation level. The effect upon the receiver is saturation of the detector at the jamming signal frequencies but only at their narrow bands within the overall limiter resonance linewidth. This effect is known as "burning a hole" in the resonance line.

Operation of the microwave limiter may best be explained by reference to a simplified equivalent circuit, shown in FIG. **3**. Referring to that Figure, the left-hand portion **50** of the circuit constitutes an input circuit which includes the antenna and which supplies signal to a normally balanced bridge **53**. Each pair of legs of the bridge contains a resistance R_Q and a capacitance C as well as a coil L inductively coupled to the input circuit. An output is taken across the diagonally opposite nodes of the bridge which connect the legs. One of the nodes is connected to a point of reference potential (e.g., "ground"). The limiter includes a resistance R_A associated with the absorption capability of the semiconductor resonance line, in one of the two pairs of legs of the bridge. This resistance is normally of zero value, so that the bridge is normally balanced, for signals outside the frequency band associated with the limiter.

Small signals within the frequency band are effective to unbalance the bridge by causing absorption within a correspond-

ing narrow band of the semiconductor cyclotron resonance line, and hence, the introduction of a non-negligible resistance value R_a into the bridge network. A large-valued signal in the band, such as an intense narrow band jamming signal, produces saturation of the resonance line at that frequency, and thereby manifests a return of the value of resistance R_a to zero. The bridge is then again in a balanced condition and the output of the bridge becomes zero, or is at least limited at that particular narrow band of frequencies.

The saturation level is principally established by the number of free carriers available, and by the collision cross section which determines the bandwidth. For the relatively small signal levels of the desired signal, passage through the limiter to the detector is assured. It is only for the intense signals exceeding the saturation level, such as the typical jamming signals, that signal passage is substantially limited, and again, this limiting (by virtue of absorption of power by free electrons in the semiconductor) occurs only at the narrow frequency band of each jamming signal.

In the limiting of microwave interference signals, the output power of the limiter is proportional to the input power until the input power exceeds a certain threshold or saturation level. Above that level, the output power is constant, and independent of input power. Since the signals are independently limited, desired signals at frequencies close to, but different from, a limited signal are passed without disturbance. The limiter is operative in a wide range of temperature, depending primarily on the specific semiconductor material selected.

I claim as my invention:

1. A tunable limiter for received signals, comprising:
a semiconductor sample containing an excess of free electrons and having a cyclotron resonance line which can be broadened by an inhomogeneous magnetic field,
means for subjecting said semiconductor to a static magnetic field,
means for subjecting said semiconductor sample to a spatially inhomogeneous RF electric field derived from RF signals,
means for simultaneously subjecting said semiconductor sample simultaneously to a static magnetic field in crossed relation to said RF magnetic field and of such magnitude as to establish a selected cyclotron resonance frequency to thereby obtain preferential absorption determined by said free electrons, over the specific narrow frequency bands occupied by the signals exceeding said saturation level.

2. The limiter of claim 1, wherein:
said static magnetic field is variable in magnitude to tune the center frequency of the limiter.

3. The limiter of claim 1, wherein:
said semiconductor is positioned in a microwave cavity within which all of said fields are present.

4. The limiter of claim 1, wherein:
said semiconductor comprises germanium having approximately 10^{17} free electrons per cubic centimeter.

5. The limiter of claim 1, wherein:
said semiconductor comprises indium antimonide having approximately 10^{17} free electrons per cubic centimeter.

6. The limiter of claim 1, further including:
means for subjecting said semiconductor to a separate RF electric field of preselected intensity to establish said saturation level at a desired value.

7. A method of limiting jamming signals in a RF receiver, comprising:
producing a static magnetic field in a waveguide while simultaneously applying a spatially inhomogeneous RF magnetic field orthogonal to said static magnetic field in response to RF signals in said waveguide, and
disposing a semiconductor in said waveguide for simultaneous subjection to both of said fields, said semiconductor having an excess of free electrons, for preferential absorption of power by said semiconductor from said electric field at specific discrete frequencies of signals exceeding a saturation level established by said free electrons, for preferential limiting at said frequencies.

8. The method according to claim 7 further including:
varying the magnitude of said static magnetic field to vary the center frequency of the band of frequencies over which said limiting is achieved.

9. The method according to claim 8 further including:
varying the collision time of said free electrons to vary said band of frequencies over which limiting is achieved.

10. The method according to claim 7 further including:
applying a separate RF electric field to said semiconductor to set the saturation level to which received signals are to be limited.

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