

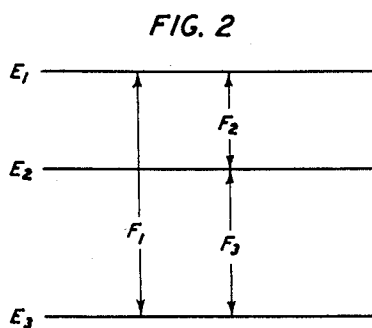
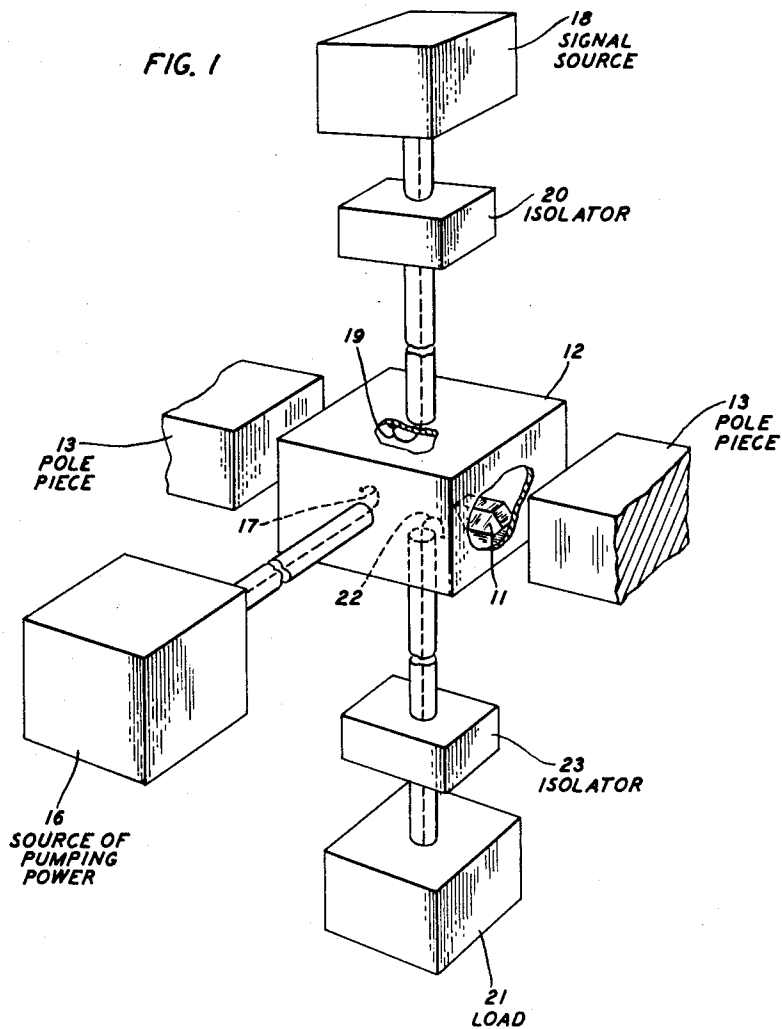
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NON-LINEAR REACTANCE AMPLIFICATION

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## NON-LINEAR REACTANCE AMPLIFICATION

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1 Claim. (Cl. 330—5)

This invention relates to arrangements which utilize a nonlinear reactance element.

In a paper published in the Proceedings of the I.R.E. entitled "Some General Properties of Nonlinear Elements," pages 904 through 913, July 1956, it is pointed out that if a nonlinear reactor is supplied with power of a high frequency and power of a low frequency, it can be made to present a negative resistance into the low frequency source circuit.

Amplifiers operating in accordance with related principles and employing the nonlinear reactive properties of ferrites, i.e., ferromagnetically resonant materials, are disclosed in copending application Serial No. 640,464, filed February 15, 1957, by H. Suhl.

The present invention is directed to amplifying arrangements which involve the use of a different class of nonlinear reactors. In particular, a feature of the preferred form of the invention is a nonlinear reactor comprising a medium which includes a large number of weakly interacting particles each of which is characterized by at least three possible quantum states. It has been found that such a medium when confined in a nonradiating enclosure which is suitably supplied with wave energy of a frequency capable of inducing transitions between two of three states can act as a nonlinear reactance for coupling to other transition frequencies of the medium because of the reaction on the medium of the change in field produced in the enclosure by the medium's electromagnetic moment. Typical of such a medium is a paramagnetic salt whose paramagnetic ions can be characterized by at least three spin states, such as gadolinium ethyl sulphate. As used in this application, the term "paramagnetic" is used in the manner now familiar to workers in solid state physics to denote a magnetic material which does not possess a spontaneous magnetic moment, i.e. there is an absence of the exchange field providing an interaction tending to make the magnetic moments line up the same way in the absence of an applied magnetic field as is characteristic of ferromagnetic materials. See Kittel's "Introduction to Solid State Physics," page 160, John Wiley and Sons (1953 edition).

In an illustrative embodiment of the invention, a paramagnetic crystal of this kind is positioned within a cavity and subjected to a steady magnetic field such that the crystal includes a large number of weakly coupled atoms or ions each of which has a spin system characterized by at least three discrete levels. The cavity is designed to be resonant near each of the three frequencies which correspond to the three possible transitions between different pairs of the three levels. Pumping power at the highest of its resonant frequencies is supplied to the cavity. Input signal power at another of its resonant frequencies is also supplied to the cavity. Output power at either the signal frequency or the third resonant frequency is then abstracted from the cavity.

The invention will be better understood from the following more detailed description taken in conjunction with the accompanying drawing in which:

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Fig. 1 shows in schematic form an amplifying system in accordance with the invention;

Fig. 2 is an energy level diagram of the medium used in the system shown in Fig. 1 to serve as the nonlinear reactance.

With reference now to the drawing, in the arrangement 10 shown in Fig. 1, a paramagnetic crystal 11 of suitable composition is positioned within a multiresonant cavity 12. Typically, the crystal may be several percent gadolinium ethyl sulphate, a paramagnetic salt, diluted in the lattice structure of lanthanum ethyl sulphate, an isomorphous diamagnetic salt. The properties of crystals of this kind are described fully in an article entitled "The Paramagnetic Resonance Spectra of Gadolinium and Neodymium Ethyl Sulphates" in the Proceedings of the Royal Society of London, A 223, 15 (1954). Such dilution is useful to control the magnetic dipole-dipole interaction between neighboring paramagnetic ions by increasing their average separation. The crystal chosen needs to have a large number of weakly coupled particles which are capable of at least three quantum states. The composition described will be characterized by a large number of weakly coupled paramagnetic ions whose spin system in the presence of a magnetic field will exhibit at least three discrete spin states corresponding to levels  $E_1$ ,  $E_2$  and  $E_3$ , respectively, as shown in Fig. 2. The cavity is designed to be resonant in three uncoupled modes. The frequencies of such modes should be slightly different, typically no more than several percent, from the three transition frequencies  $F_1$ ,  $F_2$ , and  $F_3$ , each of which satisfies Planck's Law with respect to the separation between the appropriate pair of levels as is illustrated in Fig. 2. For convenience, the resonant frequencies will be designated  $f_1$ ,  $f_2$ , and  $f_3$ , respectively. It is found necessary to operate slightly off the transition resonances to keep the resistive component of the sample's impedance low and the reactive component high. As is known, the separations of the energy levels and hence the transition frequencies may be controlled by the strength of the applied steady magnetic field and the angle such field makes with the crystal axis. The steady magnetic field is established by positioning a pair of oppositely poled pole pieces 13 on opposite sides of the cavity. In particular, the magnetic polarization of each of the cavity modes should have a component parallel to the magnetic polarization of the corresponding crystal mode. Pumping power of the frequency  $f_1$  is supplied to the cavity from a local oscillator 16 by way of a coupling loop 17 in the manner known to workers in the art for exciting the corresponding mode of the cavity.

Input signal power of frequency  $f_2$  is applied to the cavity from a source 18 by way of a coupling loop 19. It is advantageous to include an isolator 20 in the signal path intermediate between the input source and the cavity to reduce the transfer of power from the cavity toward the source.

Output power is abstracted from the cavity for utilization by a suitable load 21 by the coupling loop 22. Output power may be abstracted at either the input frequency  $f_2$ , or the difference frequency  $f_3$ . The geometry and location of the coupling loop 22 are chosen to optimize coupling to the desired mode. It is also feasible to provide a pair of loops each adjusted for optimum coupling to a different one of the frequencies  $F_2$  and  $F_3$  and to abstract power at both frequencies. It is similarly advantageous to include an isolator 23 intermediate between the load and the cavity to minimize the effect of any reflections at the load.

Alternatively, it is feasible to utilize a single coupling loop both for supplying the input power and abstracting the output power to the cavity. In this case, the coupling loop supplies one arm of a circulator, other arms of

which are connected to the signal source and the load, respectively, in a manner known to workers in the art for insuring that the input power is transmitted selectively to the cavity and output power is transmitted selectively to the load. Similarly, an input connection is unnecessary if the arrangement is employed as an oscillator. In such operation, noise, typically arising in the walls of the cavity, furnishes the input signal necessary to initiate oscillations.

For most efficient operation, it is important to keep the spin lattice relaxation times between the various levels short since these relaxation times should be not much longer than the spin-spin lattice relaxation times. Some control of the spin lattice relaxation times is provided by the temperature of the crystal. However, the crystal temperature also controls the population distribution between the various levels and it is important to operate at a temperature sufficiently low that the population difference between each of the three levels involved is fairly large. This imposes an upper limit on the operating temperature and makes desirable some refrigeration of the crystal. The spin lattice relaxation time between a given pair of levels may be reduced without deleterious effect on the population distribution by the addition of an impurity whose energy system includes a pair of levels whose separation matches that of the given pair of the paramagnetic salt and whose spin lattice relaxation time is short. By the addition of several impurities each of three spin lattice relaxation times may be shortened.

It is important for efficient operation that the product of the  $Q$  of the cavity at the frequencies  $f_2$  and  $f_3$  and the "filling factor" of the crystal for such modes be high. The "filling factor" is a measure of how much of the magnetic field of the desired mode in the cavity penetrates the sample. Accordingly, it is desirable to have as large a crystal as is feasible and to position the crystal in regions of high magnetic fields of the desired mode. Similarly, the  $Q$ 's of the cavity at the modes corresponding to frequencies  $f_2$  and  $f_3$  should be high. On the other hand, the  $Q$  of the cavity at the mode corresponding to frequency  $f_1$  advantageously is lower than at the other resonant frequencies. When the sample is introduced into the cavity the electromagnetic moment of the crystal will produce a change in the field in the cavity which will react back on the sample. The change may be described as the result of the reaction of the radiation field from the sample. Analysis shows that such reaction makes it possible for the sample to act as a nonlinear reactance coupling element between natural frequencies of the sample. The reaction field is proportional to the product of the filling factor of the sample and the  $Q$  of the cavity at the driving frequency so that these are advantageously high at the frequencies to be amplified.

An arrangement of the kind described is to be distinguished from those proposed in a paper by N. Bloembergen entitled "Proposal for a New Type Solid State Maser," Physical Review, volume 104, pages 324 through 327, which involves the saturation of a paramagnetic crystal by the application of pumping power at one transition frequency to establish a negative temperature in the sample at a lower transition frequency. Since no saturation is involved in the instant case, higher temperatures for the sample become feasible. Moreover, in the instant case, the demands on the relaxation time relationships are less stringent, and the output power available is higher. These advantages are achieved at the expense of an increase in the requirements on the cavity which now should be near to resonance at three transition frequencies and in the amount of driving power necessary.

It is feasible to utilize various other paramagnetic crystals in the manner described. For example, nickel fluosilicate is another paramagnetic salt which includes ions having the desired energy system in an applied mag-

netic field. The properties of this material are described in a paper entitled "The Paramagnetic Resonance from Nickel Fluosilicate," appearing in the Proceedings of the Physical Society of London, A 63, 29 (1950). Additionally, it should be feasible to utilize paramagnetic salts whose ions are characterized by zero field splittings so that there is avoided the need for an applied magnetic field and a polycrystalline sample may be used. Such salts are discussed in detail in copending application Serial No. 623,648, filed November 21, 1956, of K. D. Bowers.

Moreover, it is feasible, though generally disadvantageous, to utilize a medium other than a paramagnetic salt to provide the nonlinear reactance coupling. In particular, it is feasible to utilize gases which are medium weight symmetric tops, such as deuterated ammonia  $ND_3$ , phosphorous trifluoride  $PF_3$  and phosphene  $PH_3$ , known by workers in the art to include electric dipoles capable of at least three quantum states.

It should also be evident that it is feasible to employ in the arrangement shown in Fig. 1 a paramagnetic crystal whose ions will have an energy level  $E_2$  which is nearly half way between levels  $E_1$  and  $E_3$ . In this case,  $F_2$  and  $F_3$  would be nearly equal. Then it becomes feasible to utilize a cavity which is resonant only at two frequencies, since the lower of the two resonance frequencies can be nearly equal to each of the frequencies  $F_2$  and  $F_3$  of the sample. An arrangement of this kind is useful primarily for amplifying at frequencies approximately one-half the driving frequency.

It is also feasible to utilize the nonlinear reactance resulting from the reaction field in other ways. In particular, by making the reactive component of the reaction field linearly polarized at the position of a paramagnetic sample, it is possible to change from circular to elliptical the polarization of a paramagnetic resonance whereby harmonics are introduced in the polarization. Thereafter, the sample may be used to provide a nonlinear reactance coupling the fundamental to harmonic natural frequencies of the sample, and amplification at the fundamental frequency may be achieved at the expense of driving power at a harmonic frequency. Typically, in such an arrangement a paramagnetic crystal would be subjected to a magnetic field of strength such that there results a large number of paramagnetic ions whose energy system includes a pair of spin states whose separation corresponds to a transition frequency substantially equal to the range of frequencies to be amplified. The crystal is positioned in a cavity resonant near to both the transition frequency and a harmonic thereof, advantageously the second. Pumping power of this harmonic frequency is applied to the cavity such that its magnetic polarization is parallel to the applied magnetic field. Input power at frequencies near the transition frequency may then be applied to the cavity for amplification.

What is claimed is:

In combination, a solid medium comprising a crystal consisting of a diamagnetic host material doped with an isomorphous paramagnetic salt whose energy system includes at least three discrete energy levels between each pair of which there is associated a different transition frequency, each of the three transition frequencies being in the microwave range of operation, means including a cavity detuned from resonance at each of said three transition frequencies and resonant at three different frequencies for housing the solid medium and for providing an impedance whose reactive component is higher than its resistive component at each of said three transition frequencies, the sum of the two lower of said resonant frequencies equaling the highest of said resonant frequencies, means for applying to the cavity driving wave energy at the highest of said resonant frequencies of the cavity, and means for applying signal wave energy to said cavity at one of the two lower resonant frequencies of the cavity

and for abstracting from the cavity output wave energy at one of the two lower resonant frequencies of the cavity.

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