the FERROMAGNETIC MICROWAVE AMPLIFIER

By ***H. Suhl***

THE problem of detecting feeble radio signals of short wavelengths, always important in obvious defense applications, has become crucial to the study of certain astrophysical questions by means of radio astronomy. Hitherto, the lower limit on the strength of a usefully detectable signal has been the background noise generated by the more or less "hot" electrons in the vacuum tube amplifiers or crystal detectors at the head of the receiver. This difficulty has led to suggestions for replacing these more conventional input stages by atomic resonant systems, which should be much less noisy. The most famous of these are the so-called "masers" (Microwave Amplification by Stimulated Emission of Radiation): the atomic beam maser of Townes, Gordon, and Zeiger,[1] and the "Solid-State Maser" of N. Bloembergen [2] which uses a paramagnetic impurity concentration in a solid as resonant system. For purposes of comparison as well as by way of introduction, we shall begin with a simple statement of their common operating principle.

Consider a collection of similar atoms each of which has only two energy levels. When this system is in equilibrium with a constant-temperature bath, the number of atoms in the lower level will exceed that in the upper by the Boltzmann factor. The atoms in the upper level can decay to the lower by emitting a photon of frequency $1/h$ times the energy difference between the two levels, and those below can rise to the upper state by absorption of such a quantum. Since there are fewer atoms above than below, fewer quanta would be emitted than absorbed, and so the photon density would decay to zero, were it not for the fact that emission is slightly more probable than absorption. As the result some finite photon density will always exist in a system in thermal equilibrium. If now by some extraneous means the system is thrown out of equilibrium so that the upper level is more populous, more photons will be emitted than previously, and since the net rate of emission increases with the number of photons already present, this rise continues catastrophically, tending to deplete the excess population in the upper level while the extraneous agency tends to restore it. Since the energy available from this agency is limited, in practice, the photon density finally attains some finite steady value generally well above thermal, and the population in the upper state declines to a value just below that of the lower level. The system is then said to oscillate. To convert it into an amplifier, it is necessary to provide an "output load", a sink into which the photons can disappear, so that the total absorption (by the lower-state atoms + the output load) exceeds the emission. Oscillation will then cease. The population in the upper state will then again exceed that in the lower state; yet the system is stable, since the extra absorptive load restores the balance in favor of absorption. A signal applied in the form of extra photons will now cause more emission from the upper state than absorption by the lower. The excess, itself proportional to the number of applied photons by a certain factor, will appear across the output load. Clearly, if the system is not too far below its oscillation threshold, this factor can exceed unity, so that amplification is achieved. In the atomic beam maser the population excess in the upper state is produced by actually sorting out the atoms in the upper state from a mixed beam containing both kinds. In the solid-state maser of Bloembergen a three-level scheme is used. By applying sufficient microwave power ("the pump") at a frequency $1/h$ times the energy difference between the highest and lowest levels, it is possible to increase the population in the upper level far above its thermal value, up to a maximum of one half the sum of the equilibrium values of the lowest and highest levels. With a judicious choice of substances, crystal orientation, etc., the middle level is then less populous than the highest state, and amplification can be obtained as before.

The principle of operation of the ferromagnetic amplifier is quite different. Since ferromagnetism is a cooperative phenomenon involving all the odd 10^{22} or so spins per cubic centimeter of sample, this amplifier is most appropriately described, for technical purposes, by a classical analysis. Instead, we examine a quantum sys-

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tem analogous to it, partly because this places into focus the way in which it differs from masers, and partly for the sake of possible future developments which might involve quantum processes.

Let us place the same two-level system as before into a double-mode microwave cavity which is resonant to two frequencies f_1, f_2. The first important difference is that we may allow all the atoms to be in the ground state. We now apply a "pump frequency" $f_p = f_1 + f_2$, which, for efficiency, but not necessarily, should equal E/h. The following sequence of events can now occur: a representative "atom" absorbs one photon at frequency f_p, rising to the upper state in the process. There, *without causing a change of atomic state*, its interaction with the cavity allows a photon of frequency f_1 to appear. How this is possible will presently be shown. Finally the atom emits a photon of frequency f_2, dropping back to the ground state in so doing. Thus one quantum of f_p has split into one each of f_1 and f_2. Energy has been conserved ($hf_p = hf_1 + hf_2$). The atom has not changed its final state at all but has only provided the vehicle for the process. The "intermediate" states did not conserve energy, but, according to quantum mechanics, they need not do so. The only event that sounded perhaps a trifle strange was the appearance of the photon of frequency f_1 without change of the atomic state. However, let us suppose that the "atom" is an electronic spin of one half placed into a steady magnetic field along the z axis. The two states are then those in which the spin is parallel or antiparallel to $0z$. Let us arrange the field configuration of the mode f_1, so that its rf magnetic field is also along $0z$. Then it cannot exert a torque on the spin. Therefore, as it changes the number of photons, it cannot "flip" the spin from one state to another. On the other hand, the mode f_2 can be arranged to have an rf field at right angles to $0z$. Then in changing quanta, the rf field can exert a torque, and cause the spin to change states. For the same reason, the rf field of the pump must be transverse. Not all types of interaction can give rise to photons without change of atomic state; for those that cannot, it would be necessary to provide a further frequency f_3 such that $f_p = f_1 + f_2 + f_3$. Then each intermediate emission can be accompanied by a change of state without difficulty. In either case, the appearance of light quanta in the intermediate states is only transitory, unless the final and initial states have equal energies.

In assessing the net emission it is necessary to consider not only the above sequence of events but also all possible allowed permutations, and to sum over all of them. Finally, the inverse processes, absorption of f_1 and f_2 with emission of f_p, must be subtracted. The difference will leave one with a net emission, simply because emission is slightly more probable, and the net rate is proportional to the sum of the number of quanta in f_1 and f_2 and to the number in f_p. If cavity losses are not excessive, oscillation will thus build up. The system can be converted to an amplifier, as before, by addition of an output load.

An actual ferromagnetic sample placed into a cavity and supposed to amplify may seem remote from the primitive system just considered. In actual fact its operating conditions are identical with the ones just described. We require a pump frequency f_p, preferably, but not necessarily equal to the natural frequency of the uniform precession of the magnetization in the applied dc field. The cavity must be resonant at two frequencies f_1, f_2 such that $f_1 + f_2 = f_p$. One of the two modes must have an rf field component along the dc field, the other a component at right angles to it. (See Fig. 1.) It is not hard to convince oneself in classical

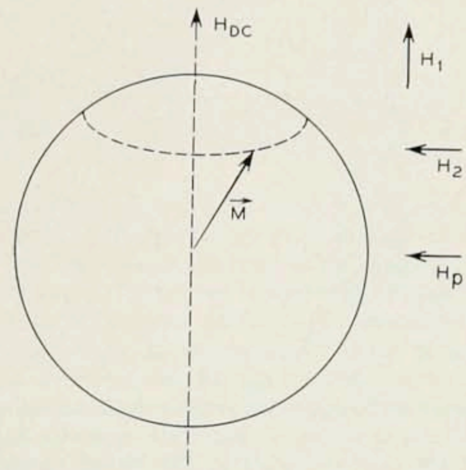

Fig. 1. Disposition of the three microwave fields ($\mathbf{H}_1$, $\mathbf{H}_2$, $\mathbf{H}_p$) at frequencies f_1, f_2, f , relative to the sample. $\mathbf{H}_p$ causes the magnetization $\mathbf{M}$ to precess about the magnetization direction. $\mathbf{H}_1$ then exerts a torque on $\mathbf{M}$ which contributes to the rate of change of $\mathbf{M}$ in the transverse plane. One such contribution has frequency $f_p - f_1 = f_2$ and radiates into the cavity, enhancing $\mathbf{H}_2$. Further interaction of $\mathbf{H}_2$ and $\mathbf{M}$ enhances $\mathbf{M}_1$, and so forth.

terms that such an arrangement can oscillate: the pump, with its rf field transverse to the magnetization direction, induces a rather wide-angle precession. A small, thermal, rf field at frequency f_2 disturbs this motion, adding to the transverse magnetization component rotating with frequency f_p a small increment at frequency f_2. Now the magnitude of the magnetization vector $\mathbf{M}$ is preserved throughout the motions of interest here. Therefore first-order transverse variations in $\mathbf{M}$ are accompanied by second-order variations of M_z, the component along the dc field. Among these second-order variations is a combination tone at frequency $f_p - f_2 = f_1$. That portion of M_z will radiate a cavity field h_z at frequency f_1. But since $\mathbf{M}$ makes some slight angle with $0z$, this field can exert a torque on $\mathbf{M}$, giving a transverse component, and since $\mathbf{M}$ itself rotates at frequency f_p, that transverse component contains the frequency $f_p - f_1 = f_2$, and radiates, enhancing the transverse cavity field at frequency f_2. This in turn enhances the field at f_1, and so oscillations can build up.

This type of operation is not the only one possible. We can in principle replace the cavity modes by certain natural modes of oscillation of the sample itself. Its magnetization is made up of a large number of inter-

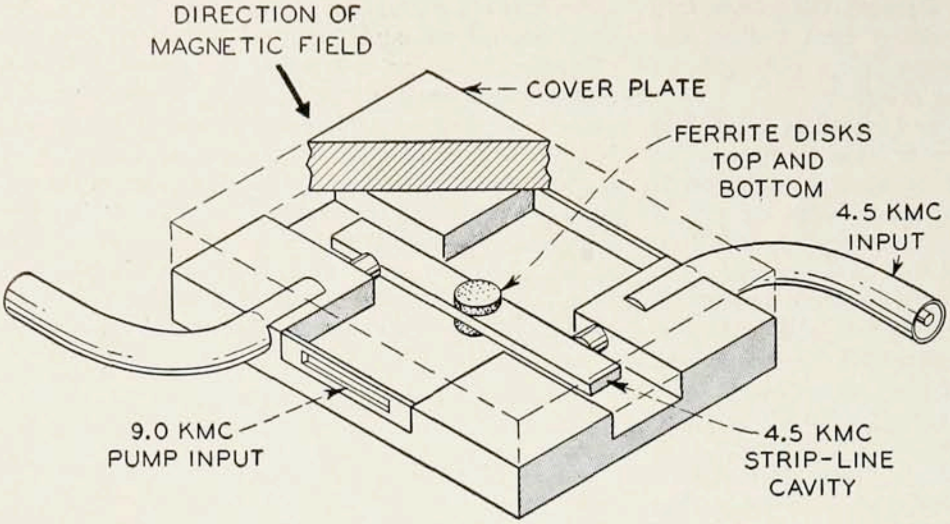

Fig. 2. Cavity configuration for ferrite microwave amplifier with purely electromagnetic modes.

acting spins, and a small local deviation of one of the spins from lineup causes the whole array to execute a small oscillation, which may be decomposed into a superposition of characteristic modes of vibration. These modes supplement those of the surrounding microwave structure in much the same way in which the "longitudinal waves" that are the natural modes of an electron cloud supplement the "transverse waves" which are the natural modes of the electromagnetic field "in vacuo". The chief difference is that the interaction here is mainly the dipole interaction between spins, rather than the electrostatic interaction between the electrons. These modes may be termed "magnetostatic".[3] In principle we may dispense with the cavity and use two of the magnetostatic modes. Indeed such an effect was involved in the resonance experiments of Damon [4] and Bloembergen and Wang,[5] who found that beyond a certain threshold power, their sample showed an anomalous absorption peak. The anomaly was later explained [6] as a decay of one quantum of their applied power into one quantum each of two magnetostatic modes. This type of operation seems attractive since the mode fields are almost entirely confined to the sample so that the "filling factor" is good and little pump power is needed to reach the threshold. However, there remain certain difficulties related to the high density of magnetostatic modes and consequent competitive instabilities from unwanted modes.[7] These difficulties can be avoided by use of an intermediate, "semistatic", type of operation, employing one electromagnetic cavity mode and one magnetostatic mode. In that case there is still some gain of filling factor over electromagnetic operation.

Recently C. L. Hogan and P. H. Vartanian [8] have pointed out an extension of the above principles. If the microwave cavity were resonant to two frequencies f_2, f_3 such that $f_p + f_2 = f_3$, the amplifier could not operate. However, if arrangements are made for a third cavity resonance at a frequency $f_p - f_2 = f_1$, then amplification can be obtained at all three frequencies, f_1, f_2, and also at f_3, which is higher than the pump frequency. The reason may be stated thus: An incoming signal at f_3 is converted to f_2 by "beating" with the pump frequency f_p. This conversion occurs without gain. However, the new signal, at f_2, can be amplified as much as desired by interaction with f_1 as described above. Finally the enhanced signal combines with f_p to yield an enhanced signal at f_3. From a quantum-mechanical viewpoint, since the equation $f_p = f_3 - f_2 = f_1 + f_2$ entails $4f_p = 3f_1 + 2f_2 + f_3$, we see that a rather high-order process is involved. Nevertheless, the threshold for oscillation of the system is, in the ferromagnet, of the same order as that of the simpler case previously discussed. Clearly, beyond the threshold, this device could be an extremely efficient harmonic generator, since essentially all the power in excess of that required for reaching the threshold is distributed among the various frequencies. In principle, one can go indefinitely high, adding more and more frequencies such that $f_p = f_3 - f_2 = f_4 - f_3 = f_5 - f_4$, etc., and oscillation or amplification can result at any of these; however, the practical difficulties are clearly considerable.

An actual model of a ferrite amplifier with purely "electromagnetic" modes was operated by M. T. Weiss [9] of Bell Telephone Laboratories, and is shown in Fig. 2. To simplify the microwave structure he chose $f_1 = f_2 = f_p/2$. Noise measurements have not yet been made. They are expected to yield noise figures corresponding roughly to the ambient temperature. However, there may be unpleasant surprises in this respect due to processes in ferromagnets of which we as yet know nothing. If so, we shall at least learn something about ferromagnetism.

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