that if one can produce $\sim 10^{15}$ electrons and holes per cc, while keeping the ionized impurity concentration below $\sim 10^{15}$/cc and the initial lattice temperature below 20°K, then the condition (2) may be met.

Assuming that the threshold for producing an instability is achieved, what happens next would seem an open question, and a most interesting one. Indeed, our lack of knowledge concerning the subsequent development of an instability is one of the prime reasons for attempting experiments in this area. In this region the behavior of the system is determined by nonlinear effects, such as the coupling between plasma modes of different wavelength. It is possible to give arguments which tend to show that the relative drift velocity will saturate near the threshold for the coherent excitation of the plasma modes, and it is clear that in time the amplitude of these modes will increase substantially over their thermal level of excitation. However, the detailed dynamic behavior of the system is not at all understood and it is, in my opinion, highly desirable that further theoretical and experimental investigations be carried out in this direction.

Pulsed Millimeter-Wave Generation Using Ferrites*

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Summary—A method is described for generating pulsed RF energy in the millimeter-wave spectrum. Low-loss garnets are used in the uniform precessional mode to store energy at *S* band and radiate at a higher frequency, which is controlled by the total magnetic field. Details are given of a *K*-band generator which operates at frequencies up to 32 kMc.

Introduction

THERE has been interest for some time in the possibility of using ferrites in simple solid-state RF generators because ferrites have a high density of electron spins, which at room temperature can store magnetic energy and transform this energy into coherent electromagnetic energy in the microwave and millimeter-wave spectrum. A number of studies[1–5] have been reported of schemes in which the energy would be supplied from a pulsed magnetic field and radiated by the ferrite in the form of short RF pulses. These investigations have disclosed both basic and technological difficulties which are inherent in the problem. These are summarized in an earlier paper on this subject by the present authors.[6]

Some recent experiments with a specific form of pulsed ferrite generator which has proved workable up to 32 kMc are described below. The basic theory and general performance characteristics to be expected from such devices are given in the earlier paper.[6] Briefly, an RF input signal is applied to an yttrium iron garnet (YIG) sphere which is adjusted for gyromagnetic resonance by means of a steady magnetic field, thus establishing a uniform precession. A pulsed magnetic field is applied along the same direction as the above dc field, thereby increasing the resonant frequency of the spins and adding energy to the spin system. During the flat top of this field pulse, the energy stored in the spin system is radiated into a coupled microwave circuit at the new higher frequency. In this type of solid-state generator then, the output frequency is higher than the input frequency; it is not harmonically related to the input frequency, and it may be varied continuously by adjusting the magnitude of the pulsed magnetic field.

The first reports of successful pulsed generation using ferrites are contained in the preceding article[6] and in

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another paper[7] describing work at the Air Force Cambridge Research Center. These projects employed approximately the scheme just described. In this early work, relatively small pulsed fields and small frequency shifts in the *S*-band region were employed with the objective of testing the basic theory. Recent efforts have been directed towards obtaining higher output frequencies and higher ratios of output frequency to input frequency. The results of this work to date have been the development of higher pulsed magnetic fields and the generation of higher frequencies, as described in the following two sections.

Pulsed Magnetic Fields

In the type of device being considered, there are simultaneous requirements on both the magnitude and the rise time of the pulsed magnetic field. The required magnitude is approximately proportional to the output frequency when that frequency is much larger than the input frequency. The required intensity of the pulsed magnetic field is approximately 10 kilogauss for RF output wavelength of 10 mm and 100 kilogauss for output wavelength of 1 mm ($F=300$ kMc). The rise time of the pulsed field should be short compared to the loaded relaxation time of the ferrite sphere, for efficient conversion of pulsed-field energy to RF output energy.[6] Ferrite material having the longest available internal relaxation time should be used, and as a rough criterion it is desirable to have a pulsed-field rise time of 30 mμsec or less.

The basic method of generating the pulsed magnetic fields is to discharge a charged transmission line through a small coil. Fig. 1 shows measured values of magnetic fields vs time on the leading edge of a field pulse reaching 10 kilogauss which is used to generate an output frequency of approximately 32 kMc when the input frequency is 4 kMc. In this instance, the transmission line consists of six RG-55/u coaxial cables connected in parallel, charged to 6.5 kv. The coil has three turns of No. 34 wire with 50-mil inside diameter.

Experiments using a 1.4 Ω parallel plate line and a very small pulsing coil with a diameter of 50 mils have produced pulsed-field magnitudes up to approximately 100 kilogauss with a rise time less than 25 mμsec. This will be used in attempts to reach higher frequencies with the pulsed generator.

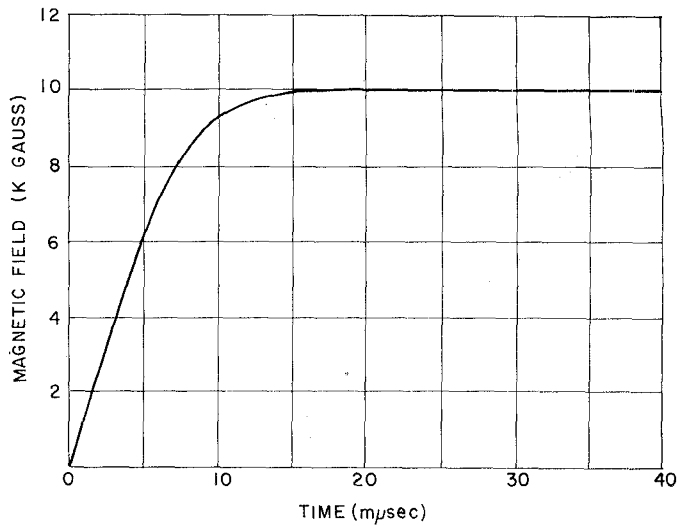

Fig. 1—Pulsed magnetic field.

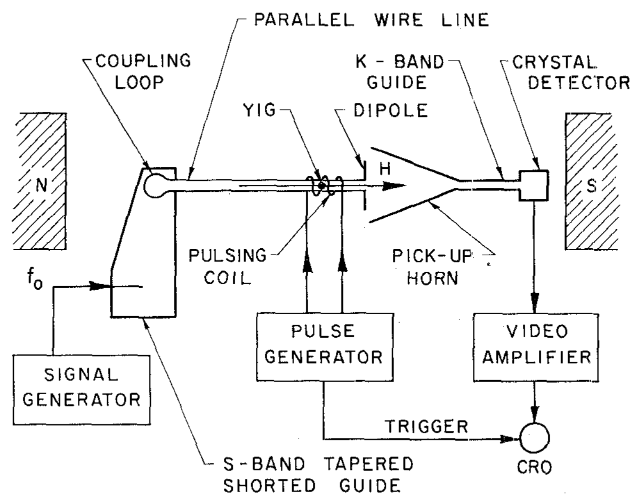

Fig. 2—Schematic diagram of pulsed generator.

Millimeter-Wave Generator

Fig. 2 is a schematic diagram of apparatus which was used in the initial attempt at millimeter-wave generation. The heart of the system is an open parallel-wire transmission line (Fig. 3) with the garnet sphere

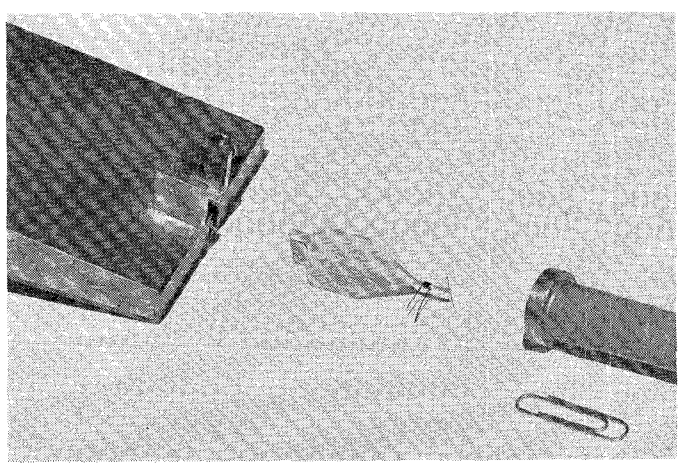

Fig. 3—Pulsed generator components.

[7] M. R. Stiglitz and F. R. Morgenthaler, "Resonance experiments with single crystal yttrium iron garnet in pulsed magnetic fields," *J. Appl. Phys.*, vol. 31, p. 37S; May, 1960.

mounted between the wires and the small pulsed field coil surrounding both the line and the garnet. The parallel, line is resonant in the $5\lambda/4$ mode at the input frequency (4 kMc) and is coupled at one end to an S-band waveguide which carries the input signal. The garnet is located near a current antinode of the S-band mode and is excited by the transverse RF magnetic field due to the input signal.

The parallel line operates in principle as a nonresonant line at the output frequency. It has very small dimensions, being constructed of 8-mil diameter wires spaced 20 mils inside, embedded in a polystyrene assembly (Fig. 3). The generated output signal travels toward the output end of the line where it is radiated by an antenna into a receiving horn. A length of waveguide leading to the detector acts as a high pass filter rejecting all signals having frequencies below its cutoff frequency, including the input signal.

This device has been operating using a single crystal garnet sphere of diameter 10 mils with a relaxation time of 100 mμsec. An output pulse was observed having frequency components above 32 kMc ($\lambda \simeq 9$ mm) using a detector waveguide with cutoff frequency of 32 kMc. The output pulse at the detector had a duration of 25 mμsec and a peak power of approximately 0.1 mw. When the system is adjusted for 15 kMc operation, the power output is 1 mw.

The qualitative dependence of the output power on variations of H_0, H_p, and input signal amplitude, indicates that the mode of operation of the device is as theoretically predicted. Power output is zero for zero input signal, and increases monotonically with input-signal amplitude. As H_0 is varied, the output reaches a maximum at the value of H_0 corresponding to ferrimagnetic resonance at the input-signal frequency and drops to zero on either side of resonance. For a given detector waveguide with known cutoff frequency f_c, there is experimental agreement between f_c and the predicted value of output frequency f, given by $f = 2.8\ H$ kMc, where H is the minimum field (in kilogauss) required to generate a detectable output signal at f_c.

During the course of these experiments a second test was conducted. The dc magnetic field was reversed, allowing the pulsed magnetic field to "invert" the total magnetic field with respect to the spins. This is a situation which has been studied with some interest[4] as a possible means of putting the ferrite in a radiative state without the necessity of an RF input signal. Theoretical studies[5] indicate that this arrangement will be unworkable because of rapid spinwave build-up. The present experiment confirms this prediction to within the sensitivity limitations of the detection system (approximately 20 μw) as no output signal was detected.

Conclusions

The above results demonstrate that RF generation at frequencies up to K band is possible with large frequency translation between input and output signals.

The open-wire line was used for two reasons. It allows the pulse coil to be placed outside the RF circuit, thereby avoiding RF shielding of the garnet by the coil. It also allows RF propagation over a wide frequency range so that testing can begin at low output frequencies and proceed in steps toward higher frequencies.

In these initial explorations efficient operation of the ferrite generator as a device was not of prime importance. Indeed, the present output is about two orders of magnitude below that theoretically available from the garnet. This may be the result of nonideal impedance behavior of the parallel-wire circuit.

Ideally, the impedance presented to the ferrite by the circuit must be carefully controlled at all frequencies between the input and output frequencies. A too-low impedance anywhere in this range can damp the ferrite prematurely and result in low power in the desired output frequency range. Such a behavior could result from spurious circuit resonances, such as are likely to exist in the present parallel-wire circuit.

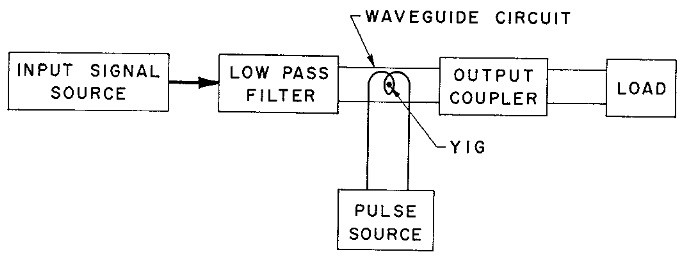

Fig. 4—Idealized generator.

Fig. 4 is a diagrammatic representation of the components of an idealized generator. The purpose of the low-pass filter is to pass the input-signal frequency while isolating the ferrite from the input circuit at all other frequencies. It should be essentially free of higher pass bands in the complete frequency range extending beyond the output frequency. The purpose of the output circuit is to provide the proper low circuit impedance in the output-frequency range so as to damp the ferrite quickly when this frequency range is reached.

For an efficient RF circuit, where careful impedance matching is possible and where inherent circuit and radiation losses are small, fully enclosed waveguides should be employed at millimeter wavelengths. It should be pointed out that this requires placing the pulsing coil inside the circuit. The effects of the coil in distorting the millimeter wave fields at the ferrite should then be investigated.