Millimeter-Wave Generation Experiment Utilizing Ferrites*

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Summary—It is estimated that at least 50 watts of peak power at 2-mm wavelength has been generated from 4-mm excitation by harmonic generation in ferrites. This experiment is similar to the frequency doubling previously reported from 9 to 18 kmc, except for some differences in optimum geometry and material. A wide range of ferrites has been used, as well as garnets and permanent magnet type materials. In carrying out this experiment it has been necessary to develop components such as a 4-mm high-power isolator, a calorimeter for measurement of the 4-mm and 2-mm power, and numerous 2-mm waveguide components.

SECOND HARMONIC GENERATION

IN previous work[1,2] it was shown that the equation of motion for uniform precession of the spin system in a magnetized ferromagnetic material, yields the second harmonic component

$$4\pi\dot{m}_{z,2\omega} = -\tfrac{1}{2}j\kappa\gamma(h_x^2 + h_y^2) \tag{1}$$

where the dc magnetic field is in the z direction, κ is the off diagonal element of the susceptibility tensor, γ is the gyromagnetic ratio, and h_x, h_y are the applied RF fields at the fundamental frequency. The solution of (1) is obtained simply as

$$4\pi m_{z,2\omega} = -\frac{\kappa\gamma}{4\omega}(h_x^2 + h_y^2) \tag{2}$$

where ω is angular frequency. If one analyzes (2), disregarding geometry factors, one sees that the maximum value of the second harmonic magnetization as a function of dc magnetic field occurs where the magnitude of κ is a maximum, and this maximum is

$$\left|\kappa\right|_{\max} = \frac{4\pi M_s}{\Delta H} \tag{3}$$

where $4\pi M_s$ is the saturation magnetization of the material and ΔH is the ferromagnetic resonance linewidth.

Eq. (3) indicates the dependence of doubling efficiency upon material properties. In a practical experiment one is concerned with other parameters, such as geometry and size. These will tend to obscure the details of the dependence indicated in (3), since the geometries are not simple and the sizes are large compared with a wavelength in the sample. However, one would expect the experimental results to agree generally with the prediction of (3). This is discussed later with the experimental results.

EXPERIMENTAL WORK

In past experiments harmonic generation has been observed from S band to C band, using a cavity geometry.[1] This experiment was characterized by a great deal of tuning difficulty and a very low conversion efficiency. In a second experiment, observations were made from X band to K band in a waveguide geometry.[2] This experiment was characterized by relative freedom from tuning difficulties and by a very high conversion efficiency. Also, in this experiment there is the possibility, in fact the probability, that a considerable amount of power was generated in harmonics higher than the second. The objective of the present experiment is to generate 2-mm wavelength energy from 4-mm energy and to study further the factors affecting the conversion efficiency. The experimental arrangement is very nearly the same as the previous waveguide experiment, and is shown in Fig. 1. Due to practical considerations there is no constricted section to reflect 2-mm energy generated in the test section and propagating toward the 4-mm source back toward the 2-mm output. Instead, resistance material is placed in the H plane of the 4-mm waveguide to absorb the 2-mm energy which is propagating toward the 4-mm source. If this were not done, part of this 2-mm energy, in some unknown phase, would be reflected back toward the 2-mm output and might be adding to or subtracting from the output. Presumably one-half of the generated 2-mm energy is lost in this way.

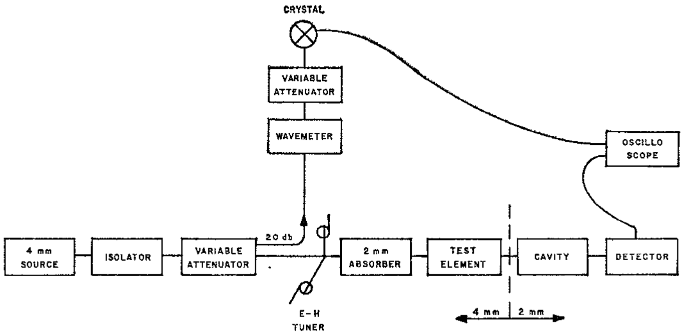

Fig. 1—Measurement block diagram for harmonic generator.

A large number of different materials and geometries have been tested in the harmonic generator. Materials

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* Manuscript received by the PGMTT, July 3, 1958; revised manuscript received, August 27, 1958. Work supported by the U. S. Army Signal Corps under Contract No. DA 36-039 SC-73278.

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[1] W. P. Ayres, P. H. Vartanian and J. L. Melchor, "Frequency doubling in ferrites," *J. Appl. Phys.*, vol. 27, pp. 188–189; February, 1956.

[2] J. L. Melchor, W. P. Ayres and P. H. Vartanian, "Microwave frequency doubling from 9 to 18 kmc in ferrites," PROC. IRE, vol. 45, pp. 643–646; May, 1957.

with high magnetizations, narrow linewidths, and high anisotropy fields were particularly sought for these experiments. In Table I the materials tested are shown in the order of their $4\pi M_s/\Delta H$ values. The output as shown in Table I is the output in millivolts from the 2-mm crystal detector. The $4\pi M_s/\Delta H$ values are estimated using values of each reported in the literature.

TABLE I

2-mm Output from Various Materials

No.	Material	Output Millivolts	$4\pi M_s/\Delta H$
1)	Yttrium iron garnet single crystal	130	180
2)	Yttrium iron garnet polycrystalline	108	27
3)	General Ceramics Ferramic G	180	17
4)	General Ceramics Ferramic R-1	80	10
5)	Ferroxcube 104	80	10
6)	Ferroxcube 106	68	6
7)	Oriented Ferroxdure	7	2

Because of variations in these quantities from sample to sample, these values are not assumed to be accurate in detail for the samples used but only indicate the trend. All of the above measurements were made using the half-disk geometry shown in Fig. 2, except for the garnet single crystal, which was not shaped at all. The garnet's general shape resembled the half disk, but it was slightly smaller than the other samples and any shaping, it was felt, would only reduce the output. The table indicates a trend in agreement with that predicted by (3), with the exception of the large output given by Ferramic G. Considering only the true ferrites, numbers 3 through 6, about which more is known than for other materials, the agreement is good in detail; that is, the measured outputs vary in almost the same proportions as the $4\pi M_s/\Delta H$ values. The oriented high anisotropy materials are quite interesting to this study from the standpoint of the reduction in applied magnetic field necessary to reach resonance. However, the outputs from all of these materials tested are disappointingly low. This is probably because the material is not highly enough oriented, so that the linewidth is extremely large.

For one material a different geometry has given greater output than the half disk gave. This is the centered post shown in Fig. 3. Ferramic G in this geometry gave an output of 270 mv, the largest output observed up to this time. This same geometry has been tried for some of the other materials, but it has not given as large an output as has the half disk. Many other geometries have been tried, such as slabs in various places in the waveguide, rods and half-rods, and others, but they have not given nearly as good results as the two geometries discussed here. The reason for this is not understood. However, the fact that the output power is extremely sensitive to very small variations in dimensions of these geometries suggests the possibility that the ferrite may be acting as a resonant cavity at the 4-mm wavelength. If so, it is possible that these geometries provide efficient coupling to the incident waveguide mode.

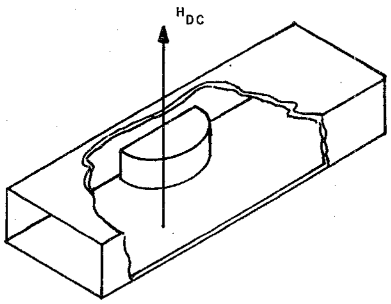

Fig. 2—Half-disk geometry. The disk height is about 60 per cent of the waveguide height, and the disk diameter is about two-thirds the waveguide width.

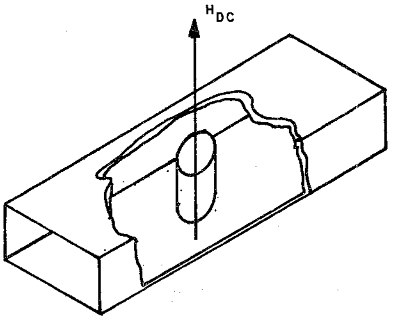

Fig. 3—Centered post geometry. The post diameter is about one-third the waveguide width, and the post height is about 90 per cent of the waveguide height.

At the pulse repetition frequency (PRF) producing the maximum average power output, the measured 2-mm power was 0.5 mw average and 7 watts peak for the centered post of Ferramic G, which produces the largest 2-mm output. However, as shown in Fig. 4, the maximum peak power does not occur at the same PRF as the maximum average power. This is because the ferrite heats up as the average power is increased, and in this case reduces $4\pi M_s$ faster than it reduces ΔH so that the important ratio in (3) is reduced. This is not always the result one obtains.[2] From Fig. 4 we see that at a PRF of 30 cps the peak power is 13 watts. Actually, the data of Fig. 4 were taken using a crystal detector and the power scale determined by an average power measurement at the peak of the average power curve with the 2-mm calorimeter. Consequently, except at this point (the point of maximum average power output) the power scale may be inaccurate because the crystal was deviating from true square law response. If this is the case, it will have the effect of increasing the true power output at lower PRF's where the peak power is greater than at the PRF where the power was actually measured. This is because the deviation of the crystal from a square law response will be towards a linear response at higher peak power levels. One must bear in mind that there are a number of losses of 2-mm power before the energy reaches the calorimeter, and these losses have not been taken into account in the results shown in

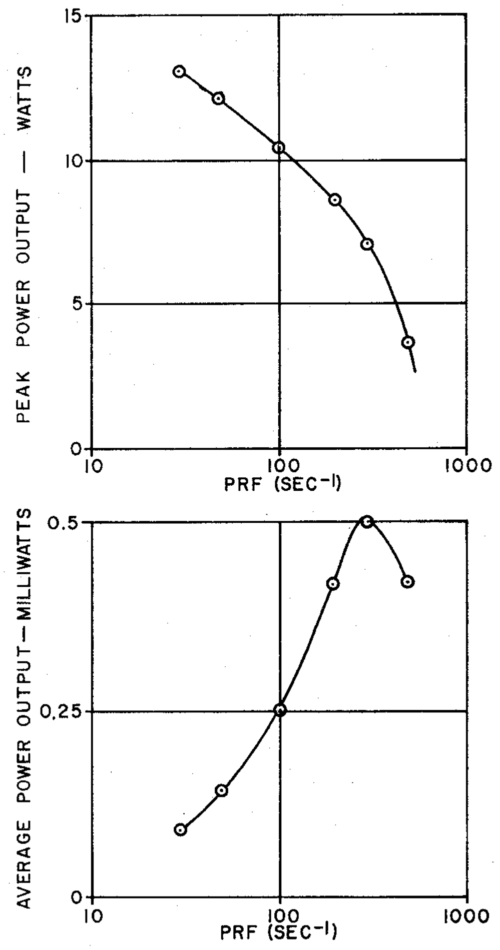

Fig. 4—Average power and peak power output as a function of the pulse repetition frequency.

Fig. 4. Half of the 2-mm energy is lost by propagation toward the 4-mm generator. Approximately half of the remainder is lost in the 2-mm transmission system and calorimeter input section. This indicates that the 2-mm energy generated is approximately four times that shown in Fig. 4 or a maximum peak power of 50 watts.

Millimeter Wave Components

During the course of this study a number of components had to be developed for the experiment. Among them is a high-power 4-mm isolator whose characteristics are shown in Fig. 5. The geometry of this isolator is of conventional high-power broad-band design[3,4] using a thin slab of ferrite against the broad wall of the waveguide, and next to it a slab of dielectric twice as thick as the ferrite. The major difference between this isolator and lower frequency models is the gyromagnetic material, which is polycrystalline oriented $BaFe_{12}O_{19}$. This material has an anisotropy field of 17 kilogauss, so that in the oriented form the applied field necessary for resonance is reduced by 17 kilogauss. Thus the magnet used for this isolator needs a field strength of only 12 kilogauss in the air gap.

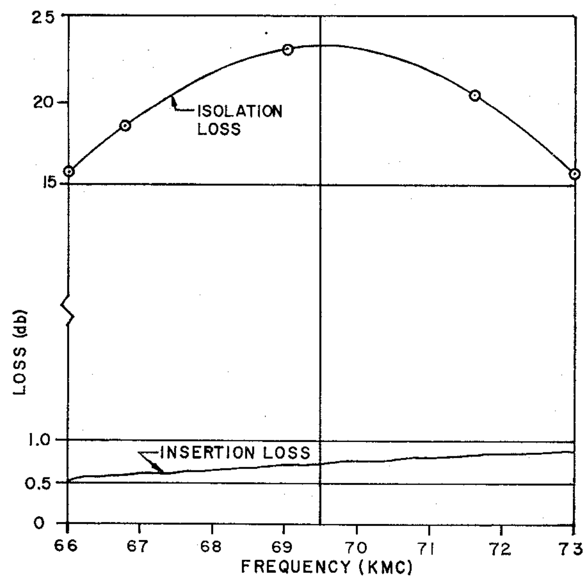

Fig. 5—Characteristics of 4-mm isolator. The input VSWR is below 1.20.

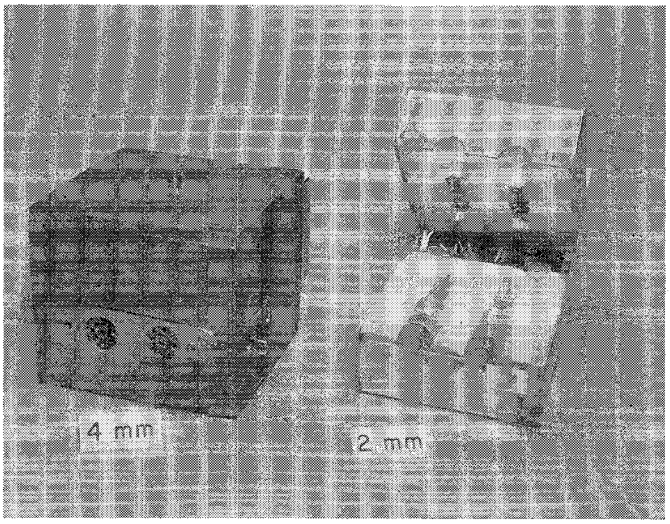

Fig. 6—Photograph of calorimeters for 4-mm and 2-mm wavelengths with 2-mm model opened to show internal construction.

A variable high-power attenuator was built by making an isolator with a moveable magnet whose position determines the insertion loss.

A 4-mm and a 2-mm calorimeter, shown in Fig. 6, were designed and constructed. In the 2-mm calorimeter the outer box is of aluminum and is filled with polyfoam for heat isolation. The waveguide input on the front is connected to a thin-walled waveguide made by milling down the walls of standard waveguide to 0.010-inch thickness. For about one inch behind the flange the waveguide is potted in an epoxy resin. In this length a $3\lambda_g/4$ slice of waveguide and resin is removed, a sheet of 0.001-inch teflon is placed over each end, and the slice is replaced in its original position separating the waveguide input from the calorimeter loads, so that heat transfer along the waveguide is minimized. The loads

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[3] M. T. Weiss, "Improved rectangular waveguide resonance isolators," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 240–243; October, 1956.

[4] G. S. Heller and G. W. Catuna, "Measurement of ferrite isolation at 1300 mc," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 97–100; January, 1958.

are tapered graphite from a carpenter's marking pencil and they have copper electrodes electrodeposited onto the tip of the taper and the back of the load. These contacts enable dc connections to be made to the load so that dc power dissipated in the load can be used for calibration of the calorimeter. The two waveguide and load units in each calorimeter are identical, so that either one can be used as the active load and the other as the reference load. To measure the temperature of the active load and compare it with the reference load, there is a string of three small bead thermistors connected in series and cemented to each waveguide. The two thermistor strings are incorporated into a 1000 cps bridge in order to measure small temperature changes easily. The remaining bridge components are installed in the small compartment on the back of the outer box. The bridge is operated as a deflection instrument, calibration curves being made of bridge unbalance as a function of time for various dc power inputs to the graphite loads. Then millimeter wave power is measured by graphing the same function with a millimeter wave input. The calorimeters will accurately measure power levels as low as 4 mw for the 4-mm model, and 0.3 mw for the 2-mm model, without taking extreme precautions regarding temperature isolations.

A number of other more conventional waveguide components were designed and constructed for 2-mm operation, and it is of interest to note that despite the short wavelength no particular difficulty was experienced in obtaining reasonable operation. Of course, some mechanical modifications had to be made due to the small size of the waveguide; however, none of these was of major significance.

CONCLUSION

High-power 2-mm energy has been generated by a ferrite harmonic generator excited by a 4-mm source. However, more 2-mm energy could be generated by further refinements in the experimental system and by the use of better ferrite materials when they become available. The material property of most importance to harmonic generation is the ratio $4\pi M_s/\Delta H$. Millimeter wave isolators, calorimeters, and other components have been designed and constructed without encountering unexpected problems due to the short wavelengths.

ACKNOWLEDGMENT

The author wishes to acknowledge the continuing assistance of Drs. J. L. Melchor and P. H. Vartanian. He also wishes to thank R. Hosking for his excellent laboratory work, including the construction of most of the delicate components.

Some Characteristics of Dielectric Image Lines at Millimeter Wavelengths*

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Summary—**The attenuation characteristics of several dielectric image lines have been calculated for the frequency range extending from 24 to 100 kmc and have been checked experimentally at 35 and 70 kmc. To obtain low attenuation at these high frequencies, dielectric materials with little loss and small size of cross section are required, while low values of the dielectric constant are also desirable. The effects of the size and shape of the dielectric cross section and of low dielectric constant are treated separately. To find proper materials with low dielectric constants several new foam plastics were investigated. Three types were found suitable for image line use, and in fact, these plastics have such good electrical and physical properties that they should be useful in many microwave applications.**

A qualitative measure of field extent is given for several image lines at 35 or 70 kmc, and various image lines and associated components are discussed. A new type of image line, called the tape line, is described.

INTRODUCTION

IN THE frequency region above *K* band, dominant-mode rectangular waveguide has the important disadvantage of high attenuation. Fig. 1 shows the theoretical attenuation for several standard waveguides. Further disadvantages are small physical size and relatively low power handling ability. These undesirable properties have stimulated the study of other types of waveguides which might have improved characteristics. One type which appears to be satisfactory is circular metal waveguide propagating the TE_{01} mode. This type has low attenuation, but since it is not a dominant-mode waveguide, mode suppressors are required. This feature adds considerable complexity to the design and construction of components and sections of guide.

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* Manuscript received by the PGMTT, June 10, 1958.

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