HARMONICS AT MILLIMETER WAVELENGTHS

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I Introduction

Two techniques for obtaining millimeter waves with sufficient power to make physical measurements have been investigated at the Columbia Radiation Laboratory. The first in point of time was to use the harmonics of the fundamental frequency directly emitted by a magnetron when it is in oscillation.[1] Harmonics up to wavelengths of 1.25 mm have been observed. The only advantage of the magnetron is in the ease of adjustment. An operator of moderate experience should be able to produce 1.5 mm radiation within a few hours using this technique.

The other method in use is to frequency multiply the power emitted by a klystron by means of a silicon-tungsten contact used as a non-linear device. This method has produced 1.5mm wavelength radiation at Columbia[2] and wavelengths up to 0.77 mm at Duke University.[3] It has the advantages that the radiation is stable in power and frequency, is monochromatic, and also is tuneable. The price paid is in a considerably greater time of adjustment and alignment, a few weeks being not at all uncommon.

II Magnetron Harmonics

Many of the technical details about producing magnetron harmonics have been reported previously.[1] Figure I is from that paper and gives the signal-to-noise ratios for the various harmonics of seven 3J31 magnetrons (which oscillate at 1.25 cm wavelength). The results are for a 1/3 Mc. bandwidth system and the signal-to-noise is called unity when the peak-to-peak noise or "grass" appearing between magnetron pulses is raised by its own height. Calibration of the crystal detectors used against a Golay Cell thermal radiation detector shows that in the region of 1.5 mm a S/N = 1 is the equivalent of about 0.5 microwatts peak power. The heavy line in Figure I is the average performance of the seven 3J31's tested and approximately follows the law

$$S/N = 10^{\lambda+1}$$

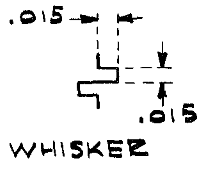
where λ is measured in millimeters.

The harmonic production is quite dependent on the magnetic field and the voltage applied to the magnetron, but generally the best harmonic power is produced where the fundamental power is greatest. A very important factor is the load into which the fundamental is working. In the work previously reported a variable load was used which could traverse one line on a Smith Chart (amplitude and phase of the reflected wave not separately adjustable). Adjustments with this load were frequently very critical which led to the belief that if the amplitude and phase could be separately adjusted the harmonic output would be considerably increased. Unfortunately this was not found to be the case when a new type of load was constructed which gave VSWR's up to 40 with the phase separately adjustable. The only change in peaks power observed was in the A-1 tubes (a pre-production model of the 3J31) which had previously tested a factor ten below the 3J31's. Both these tube types now give identical results. The only advantage of the new load is in its being easier to use and being mechanically and electrically more reliable.

The program on magnetron harmonics has now been terminated in this laboratory although this technique is still being used on one experiment, the investigation of some very broad absorptions in solids which can be widely tuned by means of a magnetic field.

III Silicon Crystal Detectors

A cross sectional view of the crystal detector is given in Figure II. This detector (as also the generator) was originally developed for the 5 - 6 mm band by E. Richter early in 1950 and has been recently used unchanged up to a wavelength of 1.5 mm.[2] The silicon and catwhisker is mounted directly in the wave guide in intimate contact with the r. f. field. The silicon is removed from burnt out 1N23 crystals (diameter 1/16") and the whisker is made from two mil tungsten wire and is given a sharp electropoint (radius less than 10^{-5} inches).



The waveguide size is RG98/U (.148x.074"). As far as is known, the polarity of the detector is immaterial.

Figure II shows a supposed six millimeter choke to keep 6 mm power from escaping down the coaxial line. However, extensive tests with various configurations including a mica bypass condenser indicate that practically no power leaks out here under any circumstances, the only effect being to tune the crystal mount to a better match. This tuning makes a maximum difference in sensitivity of a factor two at six millimeters depending on frequency. In the interest of simplicity and broadbandedness this possible improvemen has been sacrificed and the design is as shown in Figure II except that the branching radial guide has been eliminated.

Adjustment of the contact for optimizing the detector is made by rotating the post holding the silicon. This is done in the first model by scraping the point over the surface, but more recently a differential screw mechanism has been used which allows the point to be slightly retracted before rotation. This obviously will keep the shape of the point in better condition, but up to the present time the sensitivity of the detectors has not been increased with the new device despite considerable effort.

These detectors have been compared to a Golay Cell (a thermal type of infrared detector) which had been calibrated against a standard lamp in the infrared. For CW signals and equal bandwidths, the two detectors were almost equally good in the region of 1.5→2.5 mm. Therefore a signal equal to peak-to-peak noise for a bandwidth of 1 cps is about $\frac{1}{2} \times 10^{-9}$ watts (peak-to-peak noise should be divided by a factor of approximately eight to get r.m.s.). This is about 20 db worse than low level video detectors at K-band and probably at least in part is due to the effect of the barrier layer capacity shorting out the high frequency signal.

Some quantitative data has been taken at 6 mm on the effect of increasing the pressure of the whisker on the silicon. Using the differential screw mechanism, the pressure of the whisker against the silicon was gradually increased by advancing the base of the whisker. Five different whiskers were tried and they all showed the two voltage maxima at 1 mil and 5 mil spring deflections shown in Figure III, which is a composite drawing. Four had the first voltage maximum larger as shown and one the second. The behavior of the rectified current showed more variability than the voltage, but in all cases except one the 5 mil current peak was the greater. In fact, since signal-to-noise is the important quantity and this is proportional to $\sqrt{iV}$, in all the cases except one the peak at greater spring deflection is the more favorable by a rather large factor. It might also be mentioned that while the current and voltage peaks at 1 mil have their maxima at the same position, the current peak at $4\frac{1}{2}$ mils may be displaced up to ± 2 mils from the voltage peak

The VSWR remains fairly constant through the range of deflections investigated. On three whiskers it remained constant at 2 or 3 and on another it started at 1.7 and gradually rose to 3.5 at 5 mils deflection and then slowly fell to 2.9 at 8 mils. It was found that the position of the shorting plunger did not need to be changed as the pressure was increased. The video resistance of the crystal seems to begin at about 100→300 KΩ, decreases at the second voltage peak to 20→100KΩ, and then usually increases again.

This same type of behavior had been previously noticed at higher harmonics (7th and 8th), namely that two spring deflections gave approximately the same voltage signal and that the second was considerably less noisy. The second was the more favorable for stability reasons as well.

IV Crystal Harmonic Generators

Basically the harmonic generator is exactly the same as the crystal detector except that provision is made for K-band guide to intersect it at right angles. Two 0.420"x0.074" holes are made in the "b" dimension side of the crystal mount and K-band guide whose "b" dimension is tapered from .170" to .074" passes through it at this point.

Some quantitative data on the behavior of similar generators has been given.[4] Some extensions of that data and some new data will be given here.

Figure IV shows log P_n vs Log P_1, where n is the number of the harmonic. Up to a certain power level $P_n \propto P_1^n$. Then P_n begins to level off, the point at which this begins being moved toward higher fundamental powers by about 30 mw for each succeeding harmonic.

Interpretation of this behavior is rather difficult. $P_n \propto P_1^n$ would be expected for any kind of low level harmonic generator where a Taylor expansion of the i-V curve could be made. But of course twenty milliwatts is not a low level signal. In addition a Fourier analysis of an exponential i-V curve predicts that the higher harmonics should saturate at lower powers than the lower harmonics rather than vice-versa. The Fourier analysis also indicates that saturation should begin at about ten microwatts rather than twenty milliwatts.

Data has also been taken on the behavior of the harmonic generator as the pressure of the whisker is varied. A typical curve is given in Figure V. It shows second harmonic as a function of fundamental power for various spring deflections as the parameter. A very similar set of curves was obtained for third harmonic. In all, six different contacts and whiskers were investigated.

It is seen that neither the maximum harmonic power available nor the point at which saturation begins is very dependent on contact pressure. The only qualitative difference is that as the pressure is increased, the turning over of the curves is decreased.

The best spring deflection adjustments for the harmonic generator are near the first contact and then five or six mils deflection. Generally the latter would be preferable for stability, high burn out, and to avoid the necessity of carefully adjusting the fundamental power level. It is somewhat surprising that the best spring deflection for generators is closely the same as that for detectors.

Some semi-quantitative data is available on the conversion loss of the harmonic generators. On the basis of crystal current, the overall loss of a good generator and detector for the lower harmonics is about 15 db from one harmonic to the next (including.the fundamental). For example, one fairly good generator gave 210 microamps detected second harmonic, 4.5 microamps third, and 0.14 microamps fourth. On the basis of observed S/N ratios, the loss from one harmonic to the next from sixth to eight harmonics is approximately three or four db. This data can be put in the form of a semi-quantitative formula if $n \leq 8$:

$$\text{Loss} = 20 - 20n + n^2 \text{ db} ,$$

where n is the number of the harmonic. As mentioned previously, at fifth to eighth harmonic, 20 db of this loss is due to the detector.

These data are consistent with the largest S/N observed at seventh harmonic to date, a S/N of 1500 with a bandwidth of 1 cps. From the calibration of the crystal detector this is about one microwatt and gives a conversion loss for the generator of 50 db, or 70 db with the detector loss included.

V. Conclusions

Although magnetron harmonics and frequency multipliers are not very elegant or powerful methods of obtaining the shorter millimeter wavelengths, certainly they are the only methods available for this range. Many physical measurements have been made using these techniques and they have been used at wavelengths up to 0.75 mm.[3]

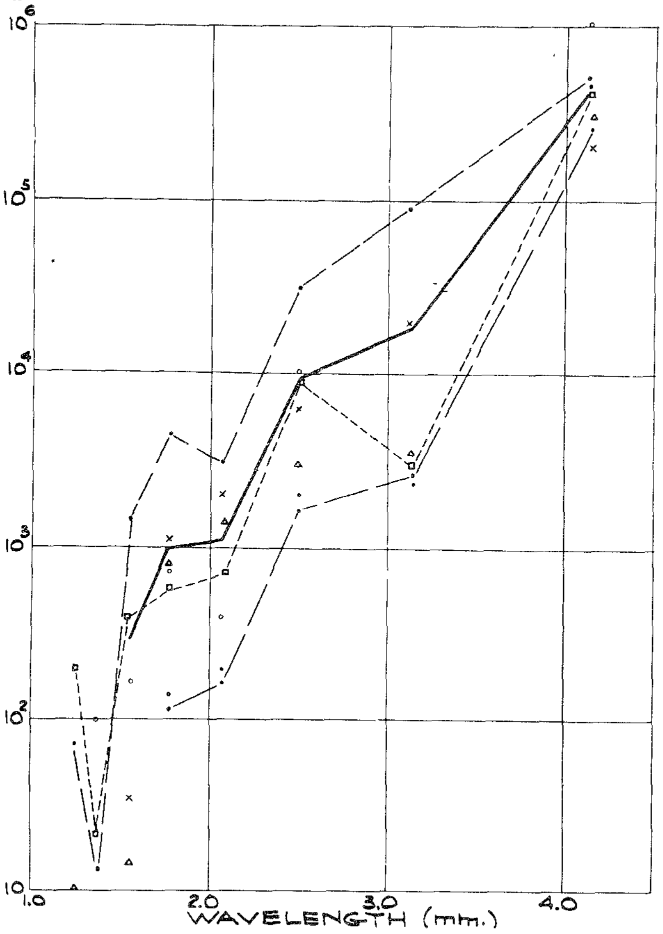


Fig. I - Harmonic production of 3J31 magnetrons.

The present paper gives some quantitative data on the performance of these devices as various paramenters are changed. It is hoped that this data will be useful in the production of higher harmonics.

Much of the data presented in this paper has been obtained by and discussed with W.R. Bennett, J.A. Klein, and B. Rosenblum.

References

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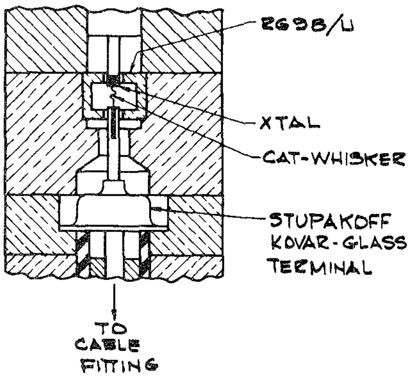

Fig. II - Sectional detail of the crystal detector.

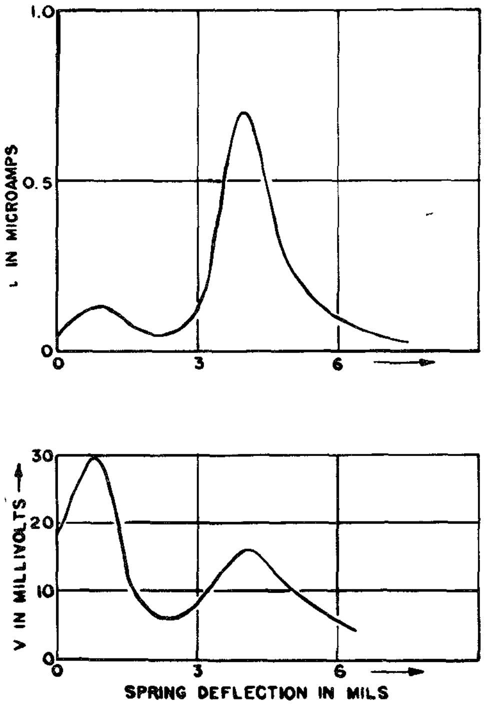

Fig. III. Crystal detector current and voltage vs. whisker deflection.

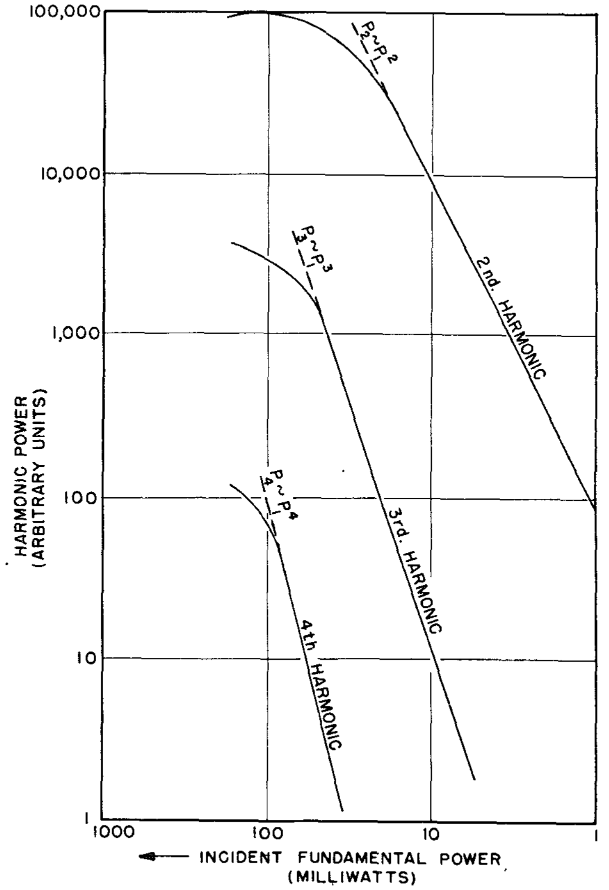

Fig. IV. Harmonic power from crystal generator vs. incident fundamental power.

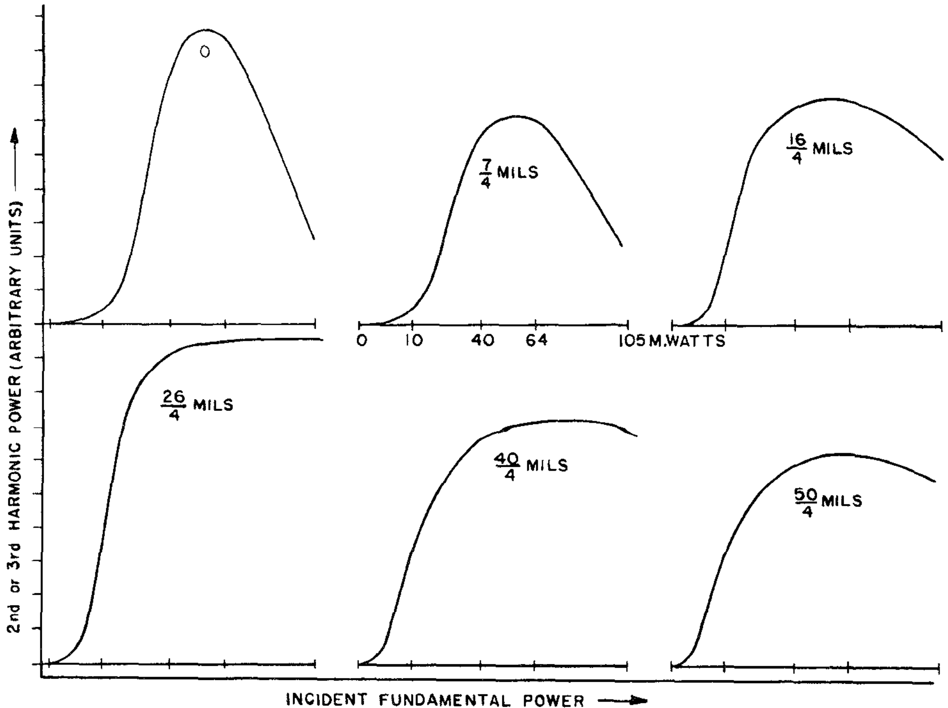

Fig. V - Harmonic power from crystal generator vs. fundamental power as whisker deflection is varied.