Performance of Three-Millimeter Harmonic Generators and Crystal Detectors*

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Summary—Because of growing applications of millimeter wave measurements, a fairly thorough investigation of what could be expected from sources and detectors in the 3 mm region was made. The sources consisted of fourth-harmonic generators from a 1.25 cm fundamental. A type of crystal holder for both harmonic generators and detectors in which a small crystal wafer is positioned in the broad wall of the millimeter waveguide, being contacted by a whisker passing across the waveguide (the open-guide type) was found to be superior in general to units using crystal cartridges or modifications thereof. Factors affecting the performance of these units have been investigated statistically. It was found that the short-circuit current sensitivity in microamperes per microwatt of a good crystal detector of the type described above is not greatly less than the value for crystals at lower microwave frequencies, so that the minimum detectable signal is about the same. As an additional result, evidence for an important effect in which the harmonic generation process degrades the signal-to-noise ratio of the source is presented and discussed.

Introduction

THE GROWING number of applications for millimeter waves in the last few years has increased the need for convenient sources and detectors of wide dynamic range. In most applications, such as microwave spectroscopy, microwave optics, or dielectric measurements, coherence and excellent monochromaticity are primary requirements. These requirements virtually dictate that the millimeter waves be produced by harmonic generation in a nonlinear element such as a crystal diode excited by radiation from a microwave vacuum tube source. There are numerous reports of such devices.[1-4]

During construction of a precision millimeter wave interferometer, it became desirable to produce a source-detector combination at 3 mm possessing large signal-to-noise ratio, freedom from spurious modulations, and convenience of operation. The latter requirement indicated a simple crystal rectifier or bolometer type of detector rather than a superheterodyne type. [Johnson and Schlesinger[5] have described a superheterodyne receiver in which the mixer crystal is driven by a (swept) local oscillator near the same fundamental frequency from which the signal harmonic is generated. The signal then mixes with the local oscillator such that a high order beat near the IF can be recovered.] If the sensitivity of the simpler crystal or bolometer should prove adequate, then of course it would be the best for the application at hand. Thus, a fairly extensive investigation of performance of such generators and detectors was made with the purpose of finding the combination of variables best satisfying the above requirements.

Measurement

The measuring apparatus is shown in Fig. 1, which is largely selfexplanatory. The slotted section was included to determine the degree of match into the multiplier produced by the E/H tuner. The waveguide lead from multiplier to detector would not support any harmonics of 1.25 cm below the fourth.

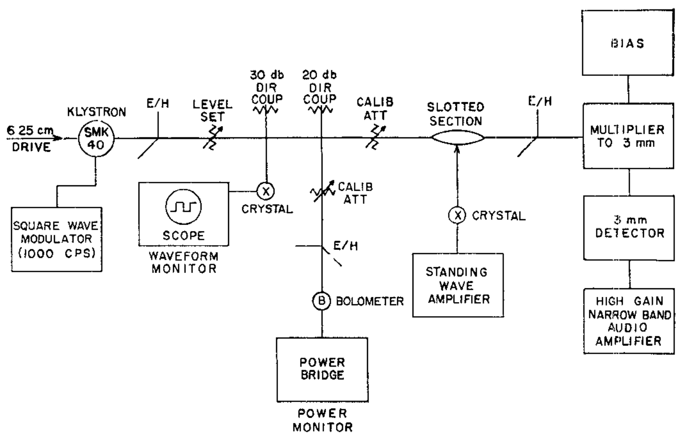

Fig. 1—Block diagram of measuring apparatus.

A drawing of the multiplier unit is shown in Fig. 2. The detector units were similar, but with the omission of the large waveguide. These units were modelled closely on the design of Johnson, Slager, and King,[3] and are designated as open-guide types. Two units of each were tested to see if significant performance differences occurred in units presumably machined in the same way from the same drawings.

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[1] C. H. Townes and A. L. Schawlow, "Microwave Spectroscopy," McGraw-Hill Book Co., Inc., New York, N. Y., 1955.

[2] J. A. Klein, J. H. N. Loubser, A. H. Nethercot, and C. H. Townes, "Magnetron harmonics at millimeter wavelengths," *Rev. Sci. Instr.*, vol. 23, p. 78; February, 1952.

[3] C. M. Johnson, D. M. Slager, and D. D. King, "Millimeter waves from harmonic generators," *Rev. Sci. Instr.*, vol. 25, pp. 213–217; March, 1954.

[4] W. C. King and W. Gordy, "One-to-two millimeter wave spectroscopy. IV. Experimental methods and results for OCS, CH_3F, and H_2O," *Phys. Rev.*, vol. 93, pp. 407–412; February 1, 1954.

[5] C. M. Johnson and S. P. Schlesinger, "Superheterodyne receiver for the 100 to 150 kMc region," Johns Hopkins Univ. Radiation Lab., Internal Memo., June 21, 1954.

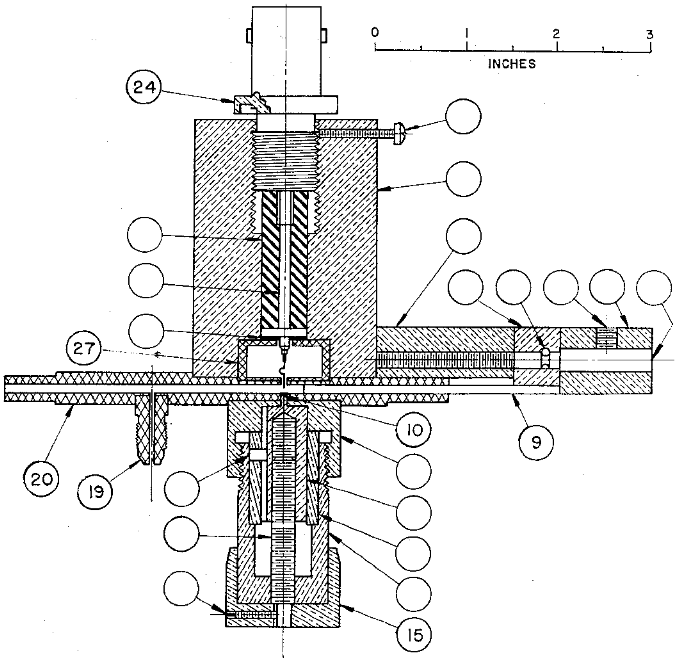

Fig. 2—Assembly of 3 mm multiplier unit. Crystal, 10; RG-66/U fundamental waveguide, 27; RG-138/U harmonic waveguide, 20; shorting stub, 9; bias connector, 24; contact adjusting knob, 15; fitting for coolant gas line, 19.

Silicon wafers extracted from several different commercial crystal cartridges were used. These included type 1N31, 1N32, 1N26, and 1N78, made by one manufacturer and type 1N26 made by another manufacturer. Although all these crystals are generally fabricated from the same source of silicon, differences in rf performance nevertheless do appear, and are the basis for classification by type number. It was asked whether differences accounting for the various classifications also produced differences in 3-mm performance. Two samples of each crystal type were tested. Difficulty was experienced in mounting 1N53 wafers on the crystal posts of our units, so that after one measurement on a 1N53 wafer indicated good but not outstanding performance, further attempts to use them were abandoned.

The question was asked whether silicon surface condition influenced performance. One surface condition, designated as "original," resulted from merely wiping the wafer clean and rinsing with alcohol. Another condition, designated as "cleaned," resulted from a thorough cleaning in concentrated sulfuric acid. A few observations were made on crystals freshly etched electrolytically in hydrofluoric acid.

Three states of whisker point condition were studied, "straight," "convex," and "used," as shown in Fig. 3. The first two were produced by slightly differing techniques of electrolytic pointing. The used point was one which had contacted a crystal once or more and had usually become blunted or bent.

Provision was made for conveniently biasing the multiplier units with various combinations of resistance and voltage.

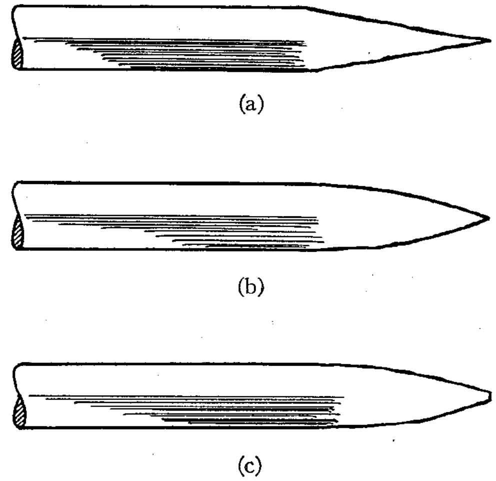

Fig. 3—Sketch of whisker point conditions: (a) straight; (b) convex; (c) used.

Multiplier performance was measured in terms of the indication of a commercial bolometer detector in RG-98/U waveguide size with taper to RG-138/U size. The observations are reported in Table I, opposite, as average 3 mm output power expressed in db above 1 μw. Because of ignorance at this wavelength about mount efficiency and the validity of dc-rf substitution, the absolute power quoted may be in error by 3 db as a best guess, but the relative values should not be seriously affected. Contact between whisker and crystal was made with only a few milliwatts incident. Contact force and incident power were then increased alternately, maintaining bias resistance and all tuning controls optimized. Each entry in Table I represents the best of two or three contacts. The best was chosen rather than an average because anyone desiring millimeter wave power will usually reject poor, average, or even good contacts until an outstanding one is achieved.

Detector observations are reported in Table II and represent the 1000 cps detected output of a detector expressed in db above 1 μv into a 600-ohm load with 5 μw average power, square-wave modulated, incident on the detector, tuning and bias controls being optimized.

What was observed was essentially the conversion efficiency of the crystals, first in converting 24 kmc power to 96 kmc power, and then in converting modulated 96 kmc power to audio power. Strictly speaking, it is not these quantities but rather the attainable signal-to-noise ratios which are of critical interest. The measurement of a signal-to-noise ratio is much more inconvenient and unreliable to make, however, so that in a practical case where the worker is seeking a good multiplier or detector, he will probably use the conversion efficiency as a criterion. The writers believe on the basis of experience that this criterion is valid; *i.e.*, the signal-to-noise ratio for given operating conditions is greater for a crystal of greater conversion efficiency, although perhaps not proportionately greater. The situation is further complicated by the dependence of both the con-

TABLE I

OBSERVATIONS ON 3 MM MULTIPLIER UNITS*

Multiplier Unit		C				D			
Crystal Condition		Original		Cleaned		Original		Cleaned	
Point Condition		Convex	Used	Convex	Used	Convex	Used	Convex	Used
1N31	a	9.5	6	—	—	8.5	4	—	—
	b	8	−4	—	—	5	−2	—	—
1N32	a	12.5	4	—	—	12	8	13.5	—
	b	11	6	—	—	12.5	—	14.5	—
1N26 Mfg. "A"	a	11	1	—	—	12	8	—	—
	b	13	3	—	—	14.5	−1.5	17	—
1N26 Mfg. "B"	a	—	—	—	—	11	—	—	—
	b	12	—	—	—	12.5	—	—	—
1N78	a	10.5	−2	—	—	9.5	4	—	—
	b	—	—	—	—	—	—	—	—

* Entries are expressed in db above 1 μw (average) of rf power with 100 mw (average) incident on the multiplier. Designations *a*, *b*, refer to assigned sample numbers.

TABLE II

OBSERVATIONS ON 3 MM DETECTOR UNITS*

Detector Unit		A				B			
Crystal Condition		Original		Cleaned		Original		Cleaned	
Point Condition		Convex	Used	Convex	Used	Convex	Used	Convex	Used
1N31	a	66	64	—	—	56	60	—	—
	b	62	48	—	—	54	56	—	—
1N32	a	60	49	—	—	46	—	—	—
	b	60	50	66	62	48	—	—	—
1N26 Mfg. "A"	a	46	50	—	—	54	—	—	—
	b	46	60	—	—	50	—	—	—
1N26 Mfg. "B"	a	48	—	—	—	—	—	—	—
	b	56	62	—	—	42	—	—	—
1N78	a	54	60	—	—	52	—	—	—
	b	—	—	—	—	—	—	—	—

* Entries are expressed in db above 1 μv into a 600-ohm load with 5 μw (average) incident on the detector. Designations *a*, *b*, refer to assigned sample numbers.

version efficiency and the generated noise on input power, and results on these effects are forthcoming from another investigation in this laboratory.

RESULTS

Statistically Significant Results

The wide range of the data as experimental conditions were varied indicated that a statistical analysis should be used to distinguish true effects from experimental fluctuations. Some parts of the experiment may be considered complete factorial experiments in that all levels of all factors of such a part are represented. The factors involved are type of silicon, number assigned to the sample (a random assignment included only for replication), the manufacturer, the multiplier (or detector) unit, the silicon surface treatment, and the whisker point condi-

TABLE III

STATISTICAL RESULTS FOR MULTIPLIERS

Factor	Result	Approximate Amount
Type Silicon	1N31 <1N32 <1N26	0<3<4 db
Assignment of Sample No.	Null	Within 3 db
Manufacturer	Null	Within 3 db
Multiplier Unit	Null	Within 3 db
Surface Treatment	Original <Cleaned	2 db
Point Condition	Used <Convex	8 db

"<" means "better than" by the indicated amount.

TABLE IV

STATISTICAL RESULTS FOR DETECTORS

Factor	Result	Relative Amount
Type Silicon	1N26 <1N32 <1N31	0<4<10
Assignment of Sample No.	Null	Within 8 db
Manufacturer	Null	Within 25 db
Detector Unit	Null	Within 8 db
Surface Treatment	Null	Within 19 db
Point Condition	Null	Within 8 db

"<" means "better than" by the indicated amount.

tion. Such results can be analyzed by the statistical technique called "analysis of variance"[6] which will supply a test as to whether either main effects or interactions of the various factors are statistically significant. The results are summarized in Tables III and IV above, in which a significance level of 10 per cent applies; that is, the existence of a positive effect would be concluded only 10 per cent of the time in the long run if in fact the true effect were null (*i.e.*, not significant). An indication of the "resolution" of the result or fineness of detection of an effect is given in each case. Interactions between factors were not found to be significant.

The generalizations worth drawing are as follows:

1) Essentially the same performance can be expected from different holders (either multiplier or detector) made from the same machine drawings.
2) Essentially the same performance can be expected from different samples of a given type of silicon, for either multiplier or detector.
3) For a multiplier, silicon from 1N26 cartridges excels that from 1N32 cartridges, which in turn excels that from 1N31 cartridges. For a detector the inverse order of silicon type is true. Silicon from 1N78 cartridges was not greatly different from that from 1N31 cartridges, for either multiplier or detector.
4) For a multiplier, the first contact of a properly sharpened point is essential. For a detector, the point condition is largely immaterial.
5) A cleaned silicon surface is beneficial in a multiplier, and may be so in a detector.

[6] See any standard text on statistics, for example, Bernard Ostle, "Statistics in Research," Iowa State College Press, 1954.

6) The resolution of the experiment was not sufficient to disclose any difference in performance due to manufacturer.

Miscellaneous Observations and Inferences

Although the above results are the only statistically significant ones emerging from the investigation, it may be helpful to enumerate a host of miscellaneous observations made during the course of this work, and which we believe to be true. Statistical testing of the hypotheses listed below was not made simply because it did not seem worthwhile.

Results with "straight" points were in every case bettered with a "convex" point, possibly because the convex point was stronger and less subject to bending.

Observations on an electrolytically etched crystal showed improved detector performance but essentially no improvement in multiplier performance.

In addition to the open-guide multiplier studied above in detail, a survey was made of other types readily available in the laboratory. The best performance of the various types is indicated for comparison below, under conditions of 100 mw average incident power, square wave modulated.

1) Open-guide type. Best output (Table I), 50 μw (Best efficiency observed at 5 mw in, 5 μw out.)
2) Windowed 1N26 cartridges. These were commercial 1N26 cartridges in which windows had been cut to expose the whisker. The cartridge was mounted in RG-66/U waveguide and the window looked into RG-138/U waveguide. Best output, 5 μw.
3) Windowed 1N53 cartridges similar to 2) above. Performance was worse than the windowed 1N26's.

Similarly, a survey of various other types of readily available 3 mm detectors was made. The best performance of the various types is indicated for comparison below. The experimental arrangement was 5 μw average incident power, square wave modulated, with 600-ohm load on the crystal detector. Figures given are microvolts across this load.

1) Open-guide type. Best output (from Table II), 2000 μv.
2) 1N53 crystal cartridges in RG-96/U (30 kmc) commercial waveguide mount, with taper from RG-96/U to RG-138/U. Best output of 20 different cartridges, 275 μv.
3) Windowed 1N26 cartridges, the window looking into RG-138/U waveguide. Best output 100 μv.
4) Wafer bolometer in RG-98/U waveguide mount, with taper from RG-98/U to RG-138/U. Bias current of about 3 ma. Output, 100 μv.
5) 1N26 crystal cartridges in RG-66/U (24 kmc) commercial waveguide mount, with taper from RG-66/U to RG-138/U. Best output of 40 different cartridges, 65 μv.
6) Windowed 1N53 cartridges, similar to 3) above. Performance was worse than windowed 1N26's.

A typical variation of 3-mm output power vs K-band input power in an open-guide multiplier with a 1N26 crystal chip and a good contact is shown in Fig. 4. 100 mw was chosen as a standard input power because it was about the maximum power that could be applied to the open-guide multipliers without causing rapid deterioration of the harmonic power with time. It was found that some contacts deteriorated quite rapidly at this power level while other contacts were stable. In general, the contact force had to be fairly heavy to minimize deterioration.

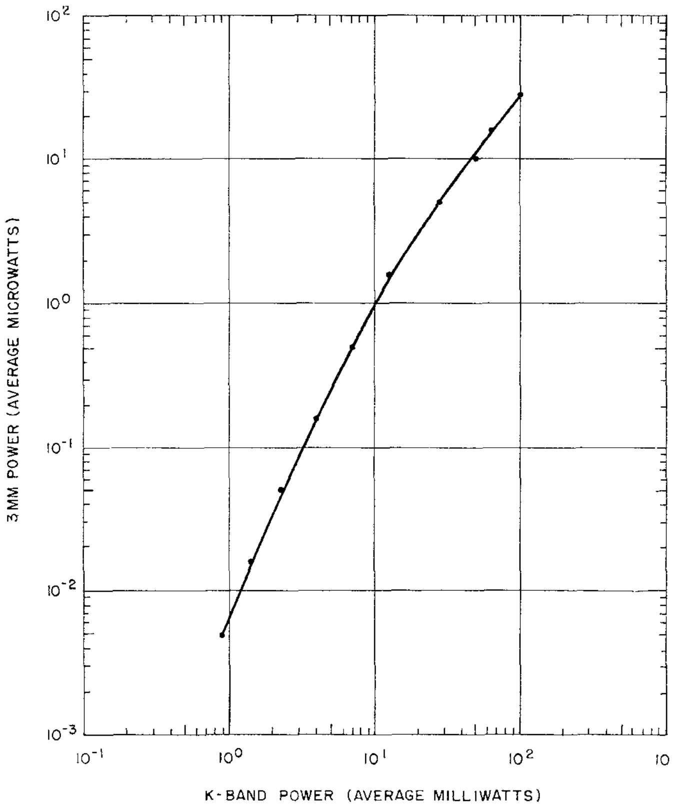

Fig. 4—3-mm output power vs K-band input power for an open-guide multiplier with a 1N26 crystal chip and a good contact.

Discussion

Sensitivity and Minimum Detectable Signal

The short circuit current sensitivity was found to be 0.75 μa/μw for the best 3-mm detector. This is to be compared with the frequently given value of 1 μa/μw for a good crystal at lower microwave frequencies, such as S-band. It is seen that the detection sensitivity has not suffered greatly by working in the millimeter region. On the other hand, as pointed out above, there are unsuitable crystal detectors whose sensitivity is as poor or worse than that of the inherently insensitive bolometer. This figure allows an estimate of minimum detectable signal of -83 dbm (5×10^{-12} w-sec$^{1/2}$) to be made assuming 1 cps bandwidth, amplifier noise figure of 4, and video impedance of 5000 ohms. Thus with the production of 50 μw average square wave modulated power, a dynamic range of 70 db is available for experimentation using careful matching and a 1 cps band.

Noise Introduced by the Multiplication Process

A measurement of the noisiness of the fourth harmonic at 3 mm was made, and is included to bring out the important point that noise is introduced in the multiplication process. We cannot quantitatively explain the mechanism of the noise introduction at this writing, but the effect is definite, and forms the subject of another current investigation in this laboratory.[7] A likely qualitative explanation is that the excitation of the multiplier crystal by large amounts (100 mw) of fundamental power produces, as is well-known, excess noise obeying the $1/f$ power spectrum. This leads to the presence of fairly strong noise currents near, for example, 1000 cps flowing in the nonlinear crystal rectifier along with currents at 24 kmc, the fundamental microwave frequency. It is supposed that the low-frequency noise currents mix with the harmonics of the 24 kmc to modulate them, thus producing noise sidebands on the 3-mm output in particular. The noise sideband spectrum will be greatest closest to the carrier, in accordance with the $1/f$ spectrum of the excess noise which produced the sidebands. When the 3-mm carrier is demodulated and observed through a filter or narrow-band amplifier we will then expect to see the demodulated noise at the filter frequency (in addition to any other noise present).

By choosing a bolometer as a square law demodulating device, and calibrating its sensitivity to power variations with a known square wave, it was possible to observe both the average power of the 4th harmonic output and the absolute magnitude of its power fluctuations caused by noise. From these data it is easy to arrive at either an effective amplitude modulation index, m, or the ratio of noise power, P_n, to carrier power, P_c for the band in use, assuming this power results from amplitude modulation alone. The same procedure was applied to the fundamental microwave, and the following results obtained reduced to 1 cps bandwidth.

$$\text{Fundamental:}\quad P_n/P_c = 0.8 \times 10^{-12}$$
$$m = 1.3 \times 10^{-6}$$
$$\text{4th Harmonic:}\quad P_n/P_c = 20 \times 10^{-12}$$
$$m = 6 \times 10^{-6}.$$

Thus by some mechanism the multiplication process has degraded the signal purity by 14 db. This degradation appears too large to be explained simply by the production and superposition at the demodulation frequency of harmonics and beats among noise components existing in the slightly impure input.

From information such as just presented, estimates may be made concerning such things as the minimum detectable modulation produced by some external modulating agency (Stark modulation in a microwave spectrometer, for example), or the smallest detectable change in signal level in an interference or transmission experiment.

Conclusion

Increasing activity in the millimeter wave region has made it desirable to investigate the characteristics of sources and detectors with a view toward optimizing available designs and describing the best performance which may be attained. The open-guide type of crystal holder has been found superior in general to more primitive types for both harmonic generators and detectors. There is a significant difference among silicon wafers extracted from various types of commercial crystals, so that choice of silicon is important. Sharpness of the whisker point is absolutely essential for a good harmonic generator. Cleanliness of the silicon surface is also significant.

The range of results produced by these factors either individually or in combination is rather large, so that the "best" combination may be some 20 db or more better than the "worst" combination. Thus, individual trial and adjustment by an experimenter is still necessary, for no specifications can yet be set down which will guarantee a given performance.

The best fourth-harmonic generators may be expected to exhibit a conversion loss rising from 30 db at 5 mw input power to 33 db at 100 mw input power. Although many of the rectifying contacts may deteriorate at input power levels above 100 mw, some may still be usable, so as to give a greater absolute value of output power.

Detector crystal sensitivity of the *best* units compares favorably with that of typical crystals for lower microwave frequencies, so that the minimum detectable signal for a given bandwidth is about the same.[8] The factor limiting the dynamic range of measurement is the maximum 3 mm power that can be produced, which is still in the microwatt region.

As an additional result, evidence of an important effect in which the harmonic generation process degrades the signal-to-noise ratio of the source was found.

[7] J. M. Richardson and J. J. Faris, "Excess noise in microwave crystal diodes used as rectifiers and harmonic generators," to be published in IRE Transactions on Microwave Theory and Techniques; July, 1957.

[8] See, for example, the discussion in Carol G. Montgomery, "Technique of Microwave Measurements," Rad. Lab. Series, vol. 11, McGraw-Hill Book Co., Inc., New York, N. Y. p. 547f; 1947.