A Submillimeter Measurement System Using a Harmonic Mixing Superheterodyne Receiver*

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Summary—A measurement system for use in the submillimeter wavelength region has been assembled and evaluated. This system utilizes two 70-Gc klystron sources and operates as high as the sixth harmonic. One of these sources provides the fundamental input power for a crystal harmonic generator which serves as the transmitter. The other klystron serves as a fundamental local oscillator for the harmonic mixing receiver. Incorporation of harmonic mixing techniques provides identification and selection of individual harmonics and simultaneously affords improved sensitivity over crystal video detection. The dynamic range of the measurement system is here defined as the difference (in db) between the maximum signal level at a specified harmonic, and that level for which the signal-to-noise ratio is unity. Dynamic ranges were measured to be 61 db at 210 Gc, 46 db at 280 Gc, 32 db at 350 Gc, and 29 db at 420 Gc. Selection of any of these frequencies is accomplished by inserting an appropriate filter in the receiver's IF amplifier. Techniques are described which can be used to improve substantially the dynamic range at the above-mentioned frequencies. The system is suitable for many types of measurements in the short millimeter and the submillimeter region, and has good possibilities for frequency extension by increasing the frequency of the fundamental signal.

Some data are included on measured transmission losses of dominant mode, and oversized, overmoded waveguide. The latter type is seen to offer advantages of reasonably low loss and simple construction when transmission over moderate path lengths is needed.

Introduction

The need for measurements in the short millimeter and submillimeter wavelength region of the spectrum has led to the assembly of a laboratory system operational at several points in this frequency range. In the past, sources were unavailable at such frequencies and, although they exist today, prices generally prohibit their widespread use. Harmonic generation then has been the only previous source of power at short wavelengths, and for many purposes may continue to be for some time. The technique of harmonic generation has always carried with it the problems of the filtering of undesired harmonics and/or positive frequency identification. These problems became increasingly difficult as the fundamental frequency and the harmonic number were increased. The system to be described here has effectively eliminated these difficulties and simultaneously has increased the receiver sensitivity beyond that achievable with crystal video detection. This method offers simple and positive identification of the harmonic being used, and has demonstrated its effectiveness up through the sixth harmonic.

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Description of Operation

The block diagram of Fig. 1 indicates the principle of operation employed. Seventy-Gc klystrons are used to furnish fundamental input power to the harmonic generator and fundamental local oscillator power to the harmonic mixer,[1] respectively. Samples of the two fundamental signals are obtained via directional couplers and are introduced through a hybrid tee to an AFC crystal mixer. An output frequency is obtained from this mixer for the AFC system which constrains the local oscillator klystron to operate at a fixed difference frequency from the primary power source. Hence, one klystron operates at a frequency f_1 and the other at f_1+f_d, where f_d is the IF frequency chosen for the AFC loop.

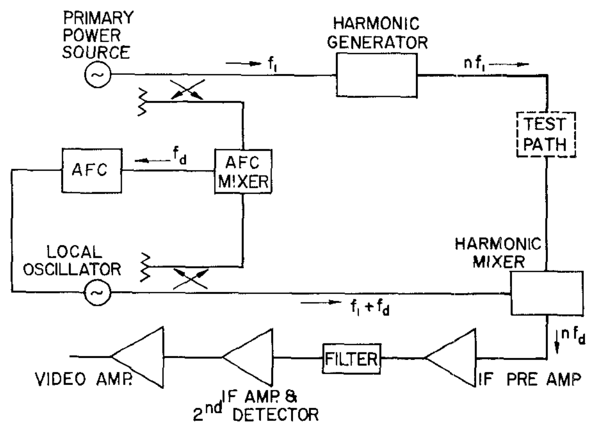

Fig. 1—Submillimeter wave propagation measurement system.

The power at frequency f_1 is then applied to a harmonic generator thereby producing harmonics at nf_i where n is the harmonic number. The output waveguide of the harmonic generator was chosen such that the second harmonic was below cutoff, and hence $n \geq 3$. No further filtering is needed, and all harmonics may then be directed through the desired test path to the harmonic mixing crystal. The fundamental LO drive for the crystal is at the frequency f_1+f_d, with harmonics at nf_1+nf_d. Of the possible sum and difference terms arising from the mixing process, those of interest are nf_d. Note that for any specified harmonic there is a unique IF frequency. The receiver's IF amplifier is chosen to pass the frequencies associated with the desired harmonic and the use of appropriately designed

[1] C. M. Johnson, "Superheterodyne receiver for the 100 to 150 kMc region," IRE Trans. on Microwave Theory and Techniques, vol. MTT-2, pp. 27–32; September, 1954.

band-pass filters then permits selection of these harmonics one at a time.

In the performance of harmonic mixing, several milliwatts of power are applied to the mixer crystal. This produces a larger crystal noise ratio than is usually obtained in conventional mixing. The principal contribution to this crystal noise ratio is local oscillator noise. Further, it is well established that the frequency distribution of this noise is such that it is greatest at the frequency of the coherent local oscillator signal and decreases with increasing separation from this coherent output. It has also been reported[2,3] that harmonic generation causes the ratio of coherent power to noise power to be less at the desired harmonic than at the fundamental input. These local oscillator noise sidebands beat with the coherent LO output to produce a substantial noise input to the IF amplifier.

One method of reducing this noise is by operating at a higher intermediate frequency.[4] The receiver IF amplifier used here was specified at 100–200-Mc bandwidth, 5.5-db noise figure, and 80-db gain. As will be seen by the trend of the measured crystal noise ratios, performance could be improved now by taking advantage of the higher-frequency, octave-bandwidth amplifiers which are currently available.

With the receiver IF determined, and harmonics 4, 5, and 6 selected for operating frequencies of 280, 350, and 420 Gc, the difference frequency for the AFC system was roughly prescribed. By choosing 30 Mc as the difference frequency at the fundamental, operation well within the band pass of the receiver amplifier was assured and band-pass filters were constructed with center frequencies of 120, 150, and 180 Mc. These filters were each 10-Mc wide and had a rejection of greater than 50 db at frequencies corresponding to the undesired harmonics. The measured characteristics of the receiver amplifier showed its gain to be flat down to 85 Mc so that the third-harmonic signal at 90 Mc was also available for use.

The method of locking the klystrons was basically that proposed by Pound.[5] A frequency discriminator circuit provides an error signal which is amplified and applied to the reflector of one of the klystrons. Since the error signal must eventually be at the reflector potential, a method similar to that described by Johnson[6] was employed. The discriminator output is first put through a dc converter, then amplified, transformed to the reflector potential and finally filtered to extract the dc once again. This method was quite satisfactory, and in closed loop operation maintained a 30-Mc difference frequency within ± 100 kc.

An alternative method is available which produces the same result with somewhat less convenience. This involves using a narrow-band receiver IF at a few hundred megacycles and changing the operating frequency of the AFC system when different harmonics are desired. The only new requirement would be a separate IF amplifier and frequency discriminator for each frequency. In some cases, this might be less costly than using a wide-band, low-noise receiver IF. It would eliminate the necessity of building filters for the receiver, and low-noise amplifiers of narrow bandwidth are more easily obtained. The advantage of positive harmonic identification would still be maintained.

The disadvantage would be that if a frequency change is desired the AFC loop must be opened and one klystron shifted in frequency and the loop closed once again. In the previously described and chosen method, a frequency change only necessitated changing an IF filter with no interruptions in the microwave circuit. The potential application would perhaps dictate the more desirable approach.

Operation and Evaluation of the Assembled System

Standard commercially available microwave components were used in all the 70-Gc circuitry except for the harmonic generator and mixer. Fig. 2 shows one of these units, which were of crossguide configuration using RG-98/U and RG-139/U waveguide. (These mixers derive from those originally described by King and Gordy.[7]) The diode junctions were formed with 0.0015-inch tungsten wire and a silicon crystal 0.010 inch in diameter, 0.004-inch thick. The pressure on the junction is adjustable with a differential screw drive. Identical units were used for the harmonic generator and harmonic mixer. The conversion losses of the individual units could not be directly measured, but may only be expressed as a product.

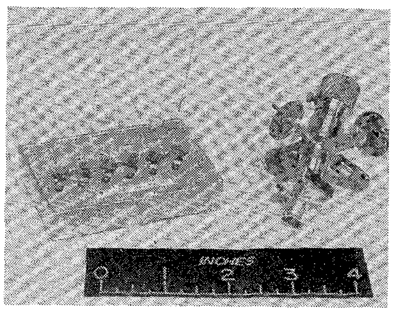

Fig. 2—Harmonic generator and mixer.

[2] J. M. Richardson and R. B. Riley, "Performance of three millimeter harmonic generators and crystal detectors," IRE Trans. on Microwave Theory and Techniques, vol. MTT-5, pp. 131–135; April, 1957.

[3] J. M. Richardson and J. J. Faris, "Excess noise in microwave crystal diodes used as rectifiers and harmonic generators," IRE Trans. on Microwave Theory and Techniques, vol. MTT-5, pp. 208–212; July, 1957.

[4] M. Cohn and J. B. Newman, "Microwave mixer performance at higher intermediate frequencies," 1959 IRE National Convention Record, pt. 3, pp. 169–176.

[5] R. V. Pound, "Frequency stabilization of microwave oscillators," Proc. IRE, vol. 35, pp. 1405–1415; December, 1947.

[6] C. M. Johnson, "Frequency Stabilization Circuit for High Voltage Klystrons," Johns Hopkins University Radiation Lab., Baltimore, Md., Internal Memorandum RL/53/IM-42; June, 1953.

[7] W. C. King and W. Gordy, "One-to-two millimeter wave spectroscopy IV," *Phys. Rev.*, vol. 93, pp. 407–412; February, 1954.

To explain this, we first define the following symbols:

Amplifier noise figure	F_{IF}
Crystal noise ratio	t
Harmonic mixing conversion loss	$L_{C(M)}$
Receiver noise figure	$F^* = L_{C(M)}(F_{\mathrm{IF}} + t - 1)$
Effective noise bandwidth	$B_{\mathrm{eff}} = \sqrt{B_{\mathrm{IF}} \times B_{\mathrm{video}}}$
Receiver sensitivity	$S_n = F^* kTB_{\mathrm{eff}}$
Power at the fundamental (70 Gc)	P_f
Harmonic generation conversion loss	$L_{C(G)}$
Transmitter power at the nth harmonic	P_n.

Among these quantities, those which are measurable are the power at the fundamental (+12 dbm), the video and IF bandwidths (40 cycles and 10 Mc, respectively), the IF amplifier noise figure (5.5 db) and the crystal noise ratio. One other quantity which can be measured indirectly is referred to here as the system dynamic range. It is the ratio P_n/S_n, or expressed in db, $(P_n - S_n)$. This is measured by using a substitution method at the IF frequency and assuming the harmonic mixing operation to be a linear process. This assumption is quite valid for the signal levels used.

No satisfactory means are available for measurements of absolute power of the order of a microwatt or less around 300 Gc. This is the fact that makes the conversion loss figures inseparable. We know

$$P_n = P_f / L_{C(G)}$$

and

$$S_n = F^* kTB_{\mathrm{eff}} = L_{C(M)}(F_{\mathrm{IF}} + t - 1)kTB_{\mathrm{eff}}.$$

Hence

$$\frac{P_n}{S_n} = \frac{P_f}{L_{C(G)} L_{C(M)} (F_{\mathrm{IF}} + t - 1) kTB_{\mathrm{eff}}}.$$

Or expressing each term in db,

$$L_{C(G)} + L_{C(M)} = P_f - (P_n - S_n) - (F_{\mathrm{IF}} + t - 1) - kTB_{\mathrm{eff}}.$$

Each of the terms on the right is known, or can in some way be measured. This, however, is as far as one can go until means are found to measure P_n.

The performance data of this particular system are indicated in Table I. The dynamic range, $P_n - S_n$, gives an indication of the utility of the system and the type of measurements which can be made. At the fifth and sixth harmonics, some improvements are needed and indeed can be achieved, before measurements involving large losses are possible. But even this first effort offers significant improvement over sensitivities which have been attained with a crystal video system, and many useful measurements are possible.

TABLE I

SYSTEM PERFORMANCE

Harmonic no. n	Frequency (Gc)	t (ratio)	$P_n - S_n$ (db)	$L_{C(G)} + L_{C(M)}$
3	210	50	61	60
4	280	37	46	81
5	350	15	32	99
6	420	8	29	104

Some Measurements on Transmission Methods

Some data on transmission losses were taken at all operating frequencies. Fig. 3 shows the measured attenuation loss through two samples of RG-139/U waveguide, expressed on a db/foot basis for comparison. The good repeatability of the data indicated that the variation between the samples did indeed exist and must be attributed to a difference in surface finish and roughness, and the lack of good dimensional tolerances in drawing the waveguide. The samples used were standard commercial coin silver and obviously the use of only very short lengths of this guide is dictated.

Other experiments involved loss measurements in oversized and overmoded rectangular waveguide. The experimental arrangement is shown in Fig. 4. Standard RG-48/U (S-band) brass waveguide was used and

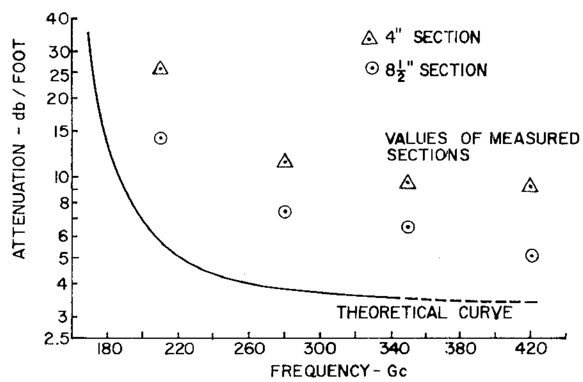

Fig. 3—Attenuation in RG-139/U waveguide.

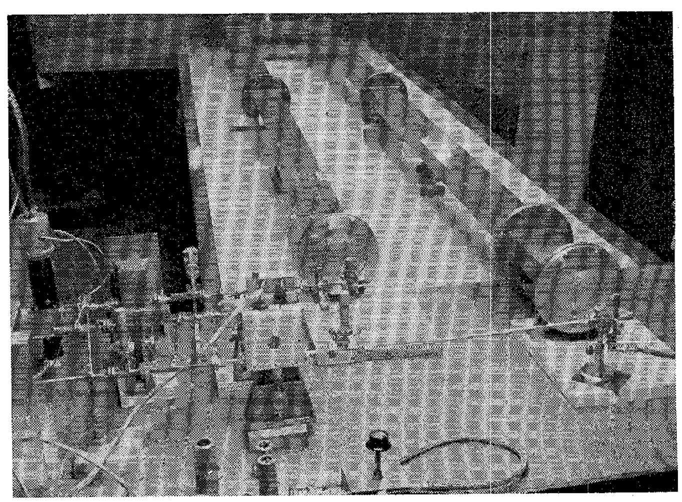

Fig. 4—Arrangement for measurements on overmoded waveguide.

measurements over lengths up to 24 feet were made. In these investigations, the launching technique used was an optical one. A pyramidal horn on the RG-139/U waveguide was used to illuminate a quartz lens which was mounted on a flange of the *S*-band guide. The horns were designed for 15-db gain at 350 Gc, and were located at the focus of the lenses. The focal length of the lenses was on the order of 2.8 inches in the frequency range used. No extraordinary precautions were taken to reduce the launching losses thus obtained, nor was any attempt made to infer the exact modal distribution within the guide. This launching is of course preferential for the lower order modes. When the initial measurements indicated losses of less than 1 db over 24 feet, the lens was diaphragmed down to a smaller aperture such that the launching of higher order modes was assured. In this condition, with a lens aperture of $\frac{3}{4}$ inch $\times 1$ inch on the nominally $1\frac{1}{2}$ inch$\times 3$ inch waveguide, losses of the order of 0.1 db/foot were measured at 350 Gc. The very low losses in the first measurements are attributed to the fact that most of the propagation path is in the Fresnel region of the lens, where the beam is quite tightly collimated, and the effect of wall losses have not really begun to show up. Had space permitted a much longer line, it is felt that loss of the order of 0.1 db/foot would have been noted.

In the case with the lens at full aperture, the total losses of launching, collecting, transmitting over 24 feet and around a 180° mitred-bend amount to $8\frac{1}{2}$ db. It is probable that the launching losses could be greatly reduced by using lensed horns. The horns would be considerably longer than the ones used here and would incorporate a lens of the proper focal length. In the transmission path tested, however, the materials used are simple, inexpensive and readily obtainable. The conclusion is that over moderate transmission paths of the order of tens of meters, where delay distortion is not a problem, this provides a quite suitable method for submillimeter propagation.

Recommendations for Extension and Improvement

Some areas where improvements can be made have already been indicated. A receiver IF of 500 to 1000 Mc should reduce the crystal noise ratio to values of less than 2. Increased sensitivity can also be obtained by narrowing the effective bandwidth. A receiver IF bandwidth of 2 Mc would be compatible with the capabilities of the AFC system up through the sixth harmonic. With the higher center frequencies, however, this becomes problematical, and it would be far simpler to reduce the video bandwidth. One could carry this to the extreme of fractional cycle bandwidths and synchronous detection methods. To avoid the addition of undue complications, however, a video bandwidth of the order of four cycles is recommended.

Another consideration is power available at the fundamental for harmonic generation. Data taken with this system indicated that $P_n \propto P_f^n$ over the ranges of power used, which is in agreement with previous work.[8] In other words, a 3-db improvement in fundamental power is seen as a 12-db improvement in the power available at the fourth harmonic. This cannot be carried on indefinitely, and will at least be limited by burnout of the diode. In the work described, however, the proportionality was valid to the extent of klystron power available at the harmonic generator, which was +12 dbm. A 70-Gc source which would furnish at least +16 dbm is readily available, and could certainly enhance system performance.

On the basis of the work already done and the foregoing suggestions for improvement, one can predict what should be a fairly readily realizable performance for a 70-Gc harmonic system. This prediction is summarized in Table II. The following assumptions made are: 1) the receiver IF is in the 500–1000-Mc region with a bandwidth of 10 Mc obtained with filters; 2) the crystal noise ratio is therefore <2 (where 2 is used for the computations; 3) the video bandwidth is 4 cycles; 4) the fundamental power at the harmonic generator is +16 dbm; and 5) that these changes are applied directly to the system which was assembled.

TABLE II

Predicted Performance of 70-Gc Harmonic System

Harmonic no. (n)	Frequency (Gc)	Improvement ($t+F_{IF}-1$) (db)	Improvement in $L_{C(G)}$ (db)	Improvement in kTB_{eff} (db)	Predicted P_n-S_n (db)
3	210	10.5	8	5	84
4	280	9.5	12	5	72
5	350	6	16	5	59
6	420	4	20	5	55

Aside from the foregoing possibility of improving on the original, there also exists the potential for frequency extension. Klystrons and other tubes in the 100-to 150-Gc range are now available and some are only moderately more expensive than 70-Gc sources. The same concept of harmonic generation and mixing from the higher fundamental should provide for considerable extension into the submillimeter region. Conversion losses for the same order harmonic will be somewhat greater when this shift is made. If the previously cited system improvements are incorporated, however, this would be more than offset. A system operating from a 140-Gc fundamental and utilizing harmonics 3, 4 and 5 should provide very useful dynamic ranges up through 700 Gc.

[8] 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.

Conclusions

In the near future, many measurements will be needed in the submillimeter region. If masers are to be developed in this range, considerable spectroscopic data on solids and gases will be required. Data are also needed on dielectric constants and loss tangents of a wide variety of materials. The latter measurement tasks may sound plebian, but they are no less necessary, and they require an operating submillimeter system. For any such usage, it is felt that the measurement system described here has many advantages, including economy and versatility. The principle has been proven and the practicality demonstrated.

Acknowledgment

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New Technique for Microwave Radiometry*

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Summary—An interference modulation technique for microwave radiometry is described. Use of the technique is considered for the development of a radiometer for tuning over a wide range of frequencies, a radiometric device for determining the absolute sensitivity of detectors over a wide range of frequencies, and a means for determining the power level of coherent sources as a function of frequency. A device using this technique does not require the use of a coherent source, and the technique is applicable to wavelengths well into the low millimeter region.

A tunable radiometer using interference modulation has been operated as a measurements system within the 50–90 Gc region. Successful performance required the use of a sensitive detector which consisted of a barretter operated in an evacuated atmosphere. A noise source having known temperature was used as the source of microwaves for determining the sensitivity of detectors as a function of frequency. It has been found that the sensitivity of barretters is greatly improved by a reduction in air pressure and that, when evacuated, a commercially available barretter will provide a sensitivity of approximately 6×10^{-11} watts for an audio bandwidth of one cycle per second. The technique discussed provides the opportunity for developing a calibrated power meter for millimicrowatt levels from coherent sources.

Introduction

A CONTINUOUSLY tunable measurements device based on an interference technique has been operated throughout the 50–90 Gc region. The instrument, which does not require the use of a coherent source, is useful for making transmission measurements as a function of wavelength; and detector sensitivity measurements can be made without the use of a power meter, per se. In fact, the technique used should also serve for measuring the output power of weak coherent sources.

Determination of detector sensitivity vs frequency throughout the low millimeter region by other techniques is a formidable task because of the low-power levels (harmonics) available, and the difficulty of obtaining harmonics throughout all of the lower millimeter region. Transmission measurements have not been possible with superheterodynes in much of the lower millimeter region because suitable coherent sources (and sensitive fast detectors) are unavailable. Use of direct-detection systems is limited by the need for a continuously tunable, band-pass filter for microwaves. The effect of a tunable filter is accomplished in the present system through the use of an interference technique and filtering in the audio range.

The heart of the new instrument is, in essence, a continuously tunable, electromechanical, band-pass filter. It has been operated throughout the 50–90 Gc region where 4-mm components could be used, but the technique used should be useful throughout the low millimeter-wave region. Operation is based on the fact that there is a one-to-one correspondence between mechanical speed and the frequency of Doppler components. Power from a microwave source is divided between two paths by a waveguide T and is recombined with a T before reaching the detector. Doppler components are produced by varying one of the paths with a trombone-shaped section which is moved back and forth by the drive rod at a nearly constant speed. Thus, an interference modulation frequency is produced which is

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