TABLE II
A COMPARISON OF RESULTS USING DIFFERENT THEORIES TO CALCULATE THE EFFECTS OF THE COMPOSITE HOLE FOR SOME WELL-KNOWN MATERIALS

Material	Cavity size (mm)				Calculated ϵ			Reference Value
	R	R_1	R_2	H	Omit the effects of Hole	Revised by Estin's results [1]	Revised by present theory	
Teflon	51.55	-	3.188	45	2.00	2.05	2.09	2.10 [7]
Quartz	51.55	2.337	3.321	45	3.61	-	3.80	3.78 [7]
Water	51.55	.432	.708	45	74.1	-	77.4	76-78 [8]
Pyrex	45.8	-	12.7	100	4.22	4.39	4.49	4.65*
Nylon	45.8	11.2	12.7	100	2.88	-	3.02	3.02*

* These values are obtained in a closed cavity by Gregory [4], Fig. 1c.

$C=0.21$). This difference is in part due to the contribution of higher order modes (20 percent to 30 percent of the total value) which were neglected in [1] and [2]. The remaining difference is due to the assumption of the boundary condition at the interface $z'=0$. The first-order perturbation theory leads to a H (6) which will probably be higher than its true value, so our results (13) and (14) will be an upper approximation of the effects of a composite hole.

2) When a dielectric tube is used to introduce the material to be measured (Fig. 1), the effects on the measurement of ϵ^* will be greatly increased with the increased value of ϵ' of the measured material. This situation is of interest on the measurement of biological samples with a high water content.

These theoretical results have already been used to revise experimental data, and the calculated values of the complex dielectric constant of various materials agreed very well with the corresponding values found in the literature [5]. For a brief comparison, some experimental results from the authors and Gregory [4] are treated by both Estin's simple theory [1] and the present method (Table II). Obviously, this more precise calculation is useful for an exact dielectric measurement. In addition, it must emphasize that wall losses of the metallic tube are not considered in this paper. At high frequency, these losses might be an important source of error in dielectric losses measurement.

REFERENCES

[1] A. J. Estin and H. E. Bussey, "Error in dielectric measurements due to a sample insertion hole in a cavity," *IRE Trans. Microwave Theory Tech.* vol. MTT-8, pp. 650–653, 1960.

[2] W. Meyer, "Dielectric measurements on polymeric materials by using superconducting microwave resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1092–1099, 1977.

[3] K. I. Thomassen, "Microwave plasma density measurements," *J. Appl. Phys.*, vol. 36, pp. 3642–3644, 1965.

[4] B. C. Gregory, "The effects of end holes and the glass tube on average electron number density measurements in a TM_{010} cavity," *Can. J. Phys.*, vol. 46, pp. 2281–2286, 1968.

[5] S. H. Li, C. Akyel, and R. G. Bosisio, "Precise calculations and measurements on the complex dielectric constant of lossy materials using TM_{010} cavity perturbation techniques." *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, no. 10, pp. 1041–1048, Oct. 1981.

[6] J. P. Montgomery, "On the complete eigen value solution of ridged waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 547–555, 1971.

[7] A. R. Von Hippel, *Dielectric Material and Application.* Cambridge, MA: MIT Press, 1954, pp. 303–370.

[8] R. F. Harrington, *Time Harmonic Electromagnetic Field.* New York: McGraw-Hill, 1961, p. 455.

Substitution Method for Swept-Frequency Measurements of Dielectric Properties at Microwave Frequencies

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Abstract—**A solid-state computer-controlled system has been used to make swept-frequency measurements of the insertion loss and reflectance of biological specimens and other media. A substitution procedure was used for direct comparison of samples to allow determination of small differences (on the order of 0.1 dB) in insertion loss and reflectance.**

I. INTRODUCTION

Several investigators claim to have observed sharp and distinct resonances in the absorption of millimeter waves by a number of biochemicals and biological preparations [1]–[5]. Some of the data suggest that the absorption spectra are significantly different for normal and malignant tissues, so that such differences might

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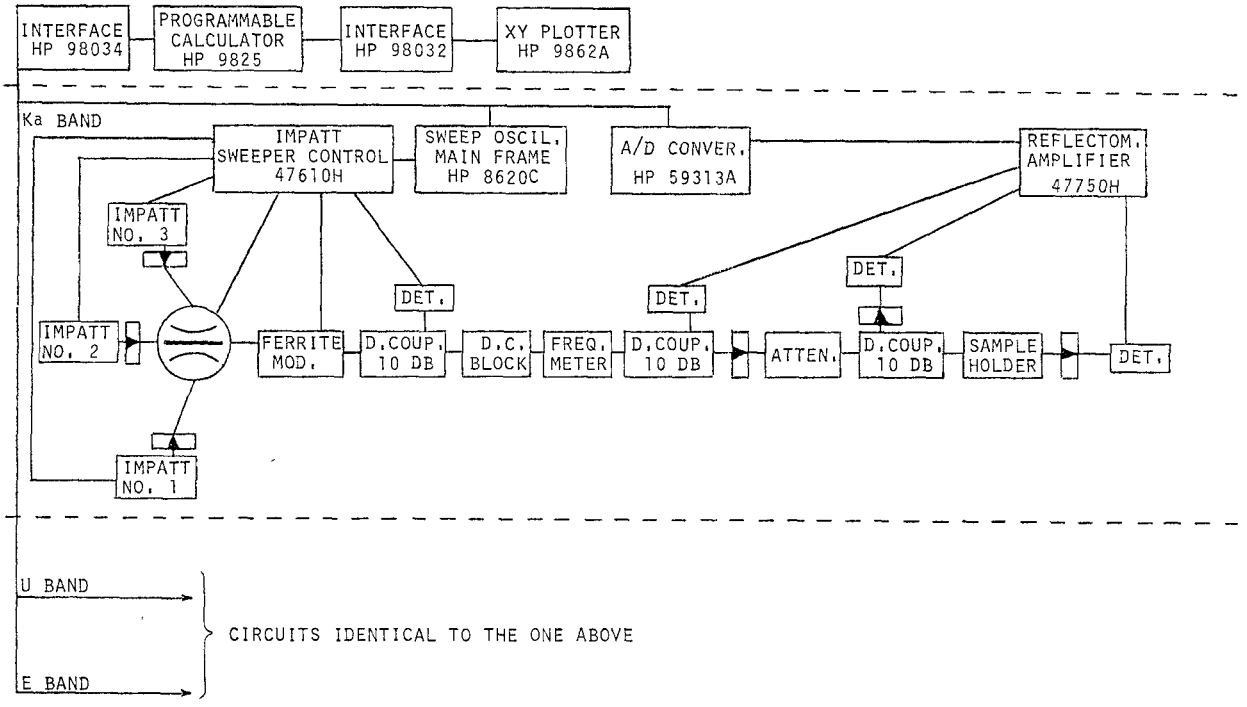

Fig. 1 Block diagram of the measurement system.

serve as the basis for the diagnosis and/or therapy of malignant diseases [2], [3], [5].

We have used a solid-state computer-controlled system to make swept-frequency measurements of the insertion loss and reflectance of biological specimens from 26.5–90 GHz. Frequency sweeping, as required in a thorough search for the alleged spectra, made it impractical to use standard procedures such as reflection profile [6] or phase measurements [7] which would allow computation of the complex permittivities of the samples. Our application required the determination of small differences (on the order of 0.1 dB) in insertion loss and reflectance of samples so that a comparison technique was used rather than conventional bridge circuits that are usable for narrow-band measurements. The system and procedures used will be described in this paper since the results of our measurements with biological specimens have been presented elsewhere [8].

II. Measurement System

Fig. 1 is a block diagram of a solid-state computer-controlled system for swept-frequency measurements that was developed jointly by us and the Electron Dynamics Division of Hughes Aircraft Company at Torrance, CA. Three similar circuits were used to cover the *Ka*, *U*, and *E* waveguide bands (26.5–40, 40–60, and 60–90 GHz, respectively). As the output frequency of the IMPATT oscillators was stepped during each sweep, digitized measurements of the incident, reflected; and transmitted powers were made and stored on magnetic tape. Sampling rates were always chosen such that the dwell time at each step was at least 50 ms, which is ten times the minimum time specified for the A/D converters.

Amplitude and frequency stability of the system have been measured several times. The extreme variations observed in amplitude were ± 0.06 dB in 1-h and ± 0.16 dB in 15-h tests. The frequency shift is typically from 1 to 6 ppm/min (about 10 MHz/h). Stability of the system was considered adequate for our measurements. Sampling intervals have generally been chosen to be 10 MHz or greater, but swept-frequency measurements of the absorption peak of a frequency meter have shown good reproducibility with intervals somewhat less than 1 MHz.

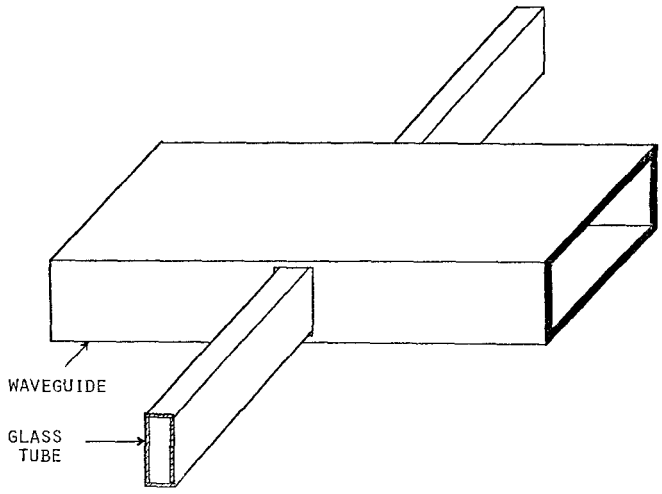

Fig. 2. Sample holder for absorption measurements.

The dc blocks were used to reduce 1 kHz noise coupled from the ferrite modulator to the detecting diodes by ground loops. This noise reduction allowed us to make several measurements with incident power as low as 0.2 μW. Several ferrite isolators were used, as shown in Fig. 1, to limit interference within the system. Spectral peaks having fairly uniform spacing which have been reported by others [1], [2], [5] have been attributed to such interference [9].

Sample holders used in the measurement system are illustrated in Fig. 2. The specimens were held in thin-walled rectangular glass tubes inserted through nonradiating slots in the narrow

TABLE I
ABSOLUTE MEASUREMENTS AT 37.5 GHz

Sample	Reflectance (dB) Calculated	Measured	Insertion Loss (dB) Calculated	Measured
Water	-2.1	-2.6	18.4	17.0
Ethanol	-5.6	-4.7	3.7	3.3
Carbon tetrachloride	-10.2	-10.6	0.44	0.5

Path length = 0.597 mm

walls of the respective waveguides. It is recognized that the presence of high-permittivity media would increase the effective electrical width of the slots so that significant leakage could occur. This effect was tested by measuring the reflected and transmitted powers both with the material extending 1 cm or more on either side of the waveguide and with the material extending only to the waveguide boundaries. Such differences in filling caused variations in reflectance and transmittance of no more than ± 0.3 dB, so the effects of leakage through the slots are considered to be minimal. In all subsequent measurements the sample holder was filled to 1 cm or more on either side of the waveguide. Measurements of relative insertion loss and relative reflectance of different samples are considered to be nearly independent of such leakage, since effects of leakage would tend to cancel when equal fill is used in all tests. The thickness of the glass walls was always less than 2 percent of the free-space guide wavelength (λ_g) at the center frequencies for each of the three bands. The samples filled the entire cross section of the three waveguides, and had total thickness on the order of $\lambda_g/10$. The glass tubes were permanently attached to the waveguide to eliminate positioning errors.

III. Measurement Procedures

The biological samples tested with the system were found to have values of insertion loss and reflectance that were largely dominated by the strong absorbance of water (10–30 dB/mm) present in the samples. Relative measurements were made by direct comparison of insertion loss and reflectance of the specimens with the solutions in which they were either dissolved or suspended. The use of a direct comparison allowed the measurement of minor differences (as low as 0.1 dB) which would not be seen in comparing absolute values individually determined for the samples.

In each measurement first the digitized outputs of the reflected and transmitted diodes are recorded during a frequency sweep with the sample in place. Then the standard medium is inserted and the outputs of the two diodes are recorded during frequency sweeps for several lower and higher settings of the variable attenuator. Interpolation is then used to determine the change in attenuation corresponding to the difference between the sample and the standard medium for both the transmitted and reflected diodes. The latter values correspond to the relative insertion loss and relative reflectance, respectively. Absolute values of insertion loss and reflectance are determined by using the empty sample holder as the standard. Generally five or more replicate sweeps were made so that means and standard deviations could be evaluated.

We have found that the accuracy of the substitution procedure is limited by the accuracy of the variable attenuator, amplitude and frequency stability of the measurement system, flatness of the oscillator power with frequency, and width of the intervals used for interpolation. If an isolator or other device causes a large variation of power at a particular frequency, then a minor drift in frequency between sample and standard frequency sweeps will cause apparent spectral peaks. Careful matching of components is required to limit such effects.

IV. Results of Measurements

The results of our swept-frequency measurements with a wide range of samples, including solutions of DNA and RNA, and suspensions of BHK21/C13 cells, *C. albicans*, *C. krusei*, and *E. coli* have already been presented [8]. All such samples were dominated by the strong absorbance of water and so appeared to be nearly identical. No samples had significantly greater insertion loss than water or significant frequency-specific phenomena such as resonances in absorption.

Table I gives the results of some additional tests made with chemicals to test the accuracy of the system for absolute measurements. Published values of the dielectric properties of water [6], ethanol [7], and carbon tetrachloride [6] were used in the calculations. It was also necessary to assume that a pure TE_{10} mode is present in the sample for the calculations. The test using carbon tetrachloride is particularly severe due to the use of a small sample thickness (0.597 mm) with such a low-loss medium.

V. Conclusions

A novel system has been used to make swept-frequency measurements of the insertion loss and reflectance of biological preparations as well as other media over the frequency range of 26.5–90 GHz. The system has good stability and low noise.

A substitution procedure developed for direct comparison of similar media in swept-frequency measurements was found to allow determination of small differences (about 0.1 dB) in insertion loss and reflectance.

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References

[1] S. J. Webb and A. D. Booth, "Absorption of microwaves by microorganisms," *Nature*, vol. 222, pp. 1199–1200, 1969.
[2] S. J. Webb and A. D. Booth, "Microwave absorption by normal and tumor cells," *Science*, vol. 174, pp. 72–74, 1971.
[3] M. E. Stamm, W. D. Winters, D. L. Morton, and S. L. Warren, "Microwave characteristics of human tumor cells," *Oncology*, vol. 29, pp. 294–301, 1974.
[4] L. Dardanoni, V. Torregrossa, C. Tamburello, L. Zanforlin, and M. Spalla, "Biological effects of millimeter waves at spectral singularities," Third Wroclaw Symp. Electromagnetic Compatibility, (Wroclaw, Poland), 1976.
[5] R. A. Lee and S. J. Webb, "Possible detection of In-Vivo viruses by fine structure millimeter microwave spectroscopy between 68 and 76 GHz,"

IRCS Med. Sci., vol. 5, p. 222, 1977.
[6] R. Van Loon and R. Finsy, "The precise microwave permittivity measurement of liquids using a multipoint technique and curve-fitting procedure," *J. Phys. D: Appl. Phys.*, vol. 8, pp. 1232–1243, 1975.
[7] J. A. Saxton, R. A. Bond, G. T. Coats, and R. M. Dickinson, "Dispersion at millimeter wavelengths in methyl and ethyl alcohols," *J. Chem. Phys.*, vol. 37, pp. 2132–2138, 1962.
[8] O. P. Gandhi, M. J. Hagmann, D. W. Hill, L. M. Partlow, and L. Bush, "Millimeter wave absorption spectra of biological samples," *Bioelectromagnetics*, vol. 1, pp. 285–298, 1980.
[9] W. D. Hershberger, "Microwave transmission through normal and tumor cells," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 618–619, 1978.

A Harmonic Mixer for the 20–40-GHz Range

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Abstract—**The design and performance of a wide-band harmonic mixer are described. The circuit is built on a microstrip substrate and uses a single GaAs Schottky-barrier diode.**

I. Introduction

Many of the emerging requirements for millimeter-wave applications involve augmentation of existing systems. Small size, in addition to low cost, is frequently crucial to the success of such an extension program. A wide-band harmonic mixer was designed and fabricated to meet the needs of such a subsystem application and the results are reported in this paper. The LO frequency is 2 GHz, the RF range is 20–40 GHz and the IF frequency is 100 MHz, nominal. The use of stripline circuits for harmonic mixers in the microwave region has been previously reported [1], [2] and similar devices built in waveguide circuits are commercially available. However, the use of hybrid, lumped element, and microstrip techniques shown here should give size and cost advantages while providing comparable performance.

II. Description of the Mixer Circuit and Construction

The circuit is shown in Fig. 1. The diode is a commercial, Alpha type DMK 6606. It is a beam-lead GaAs Schottky-barrier diode. The manufacturer's data sheet gives a capacitance of 0.1 pF and a cutoff frequency of 300 GHz at 0 V. This leads to a series resistance of about 5 Ω. The wide separation of frequencies at the three ports permits the use of simple, mostly lumped element isolation filters. Sections of transmission line are used for impedance matching except at the IF port where some lumped elements are also used.

A photograph of the harmonic mixer is shown in Fig. 2. The circuit is fabricated on a 10-mil RT/Duroid 5880 substrate. The size of the substrate is 0.475 in×0.655 in The diode is grounded on one end by a pair of plated through holes. The RF ground is enhanced by the use of $\lambda/4$ (at 30 GHz) radial sector line. A 0.7-mil-diameter gold wire serves as a grounded inductor at the RF port. The series capacitor at this port has a value of 0.1 pF, which appears small for a coupling capacitor; however, most of its reactance at RF frequency is cancelled by its "parasitic" inductance and the inductance of a ribbon used to connect it on one end. Its high reactance at 2 GHz helps in rejecting the LO signal. All the capacitors are ceramic chip type. The bias resistor is a fixed value of 600 Ω selected for optimum performance across the band.

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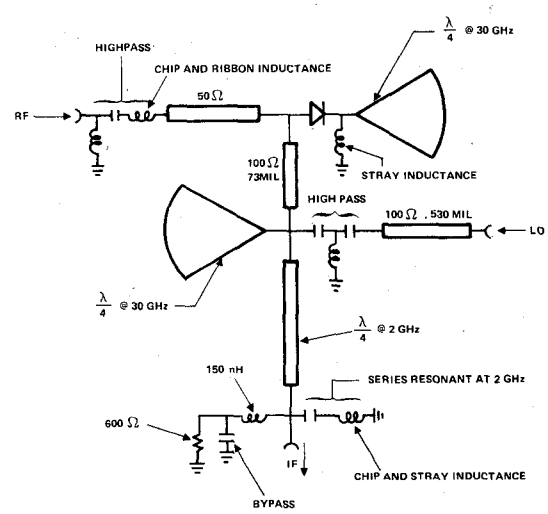
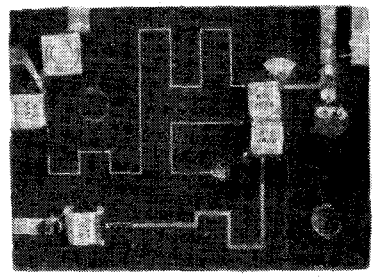


Fig. 1. Circuit diagram of the harmonic mixer.



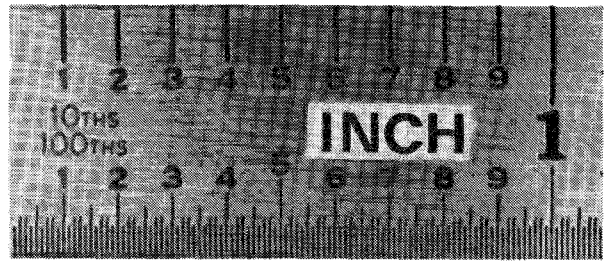


Fig. 2. The harmonic mixer substrate with all the circuit elements attached.

III. Performance

The mixer was mounted in a test housing with SSMA connectors at all three ports. A coax to waveguide transition was used at the RF port for tests. All the data reported here is for a fixed LO frequency of 2 GHz and an LO power of +20 dBm. Fig. 3 shows the conversion loss for different harmonic numbers. No adjustments were made to optimize the performance at each frequency. The conversion loss increased somewhat with lower LO power and there was no significant improvement at higher power levels. Fig. 4 shows the LO to RF isolation. A calibrated spectrum

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