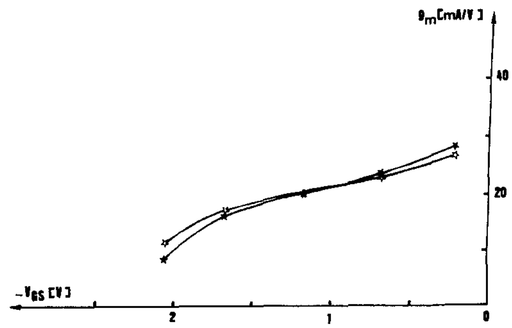

Fig. 13. Calculated g_m versus V_{GS} in the saturation region. ★: dark, ☆: light power = 0.3 mW. $N_{DD} = 1.3 \times 10^{17}$ cm^{-3}, $V_{LD} = 0$ V, $N_{DL} = 1.5 \times 10^{17}$ cm^{-3}, $V_{LL} = 0.35$ V.

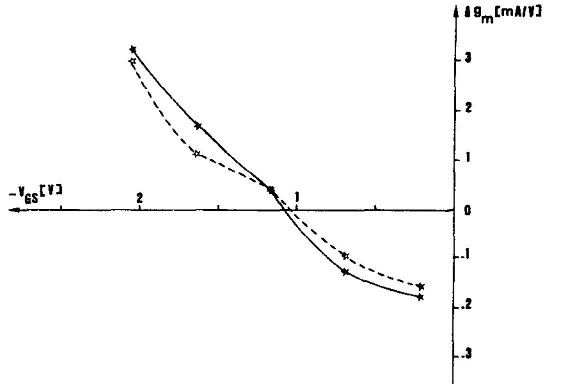

Fig. 14. ★: $(\Delta g_m)_{ex} = (g_{mL} - g_{mD})_{experimental}$ versus V_{GS} in the saturation region ☆: $(\Delta g_m)_{th} = (g_{mL} - g_{mD})_{theoretical}$ versus V_{GS} in the saturation region.

when the transistor is illuminated, can be obtained by substituting in (4)–(10) subscript D by subscript L taking into account the increase of the carrier density and the voltage V_{LL} (Fig. 13).

The free-carrier density in the light N_{DL} is experimentally obtained by measuring the slope of the dc characteristic I_D versus V_{DS} of a device without the gate biased in the ohmic region.

The comparison between experimental and theoretical values of the change in g_m due to illumination (Fig. 14), i.e.,

$$(\Delta g_m)_{ex} = g_m(\text{under illumination, experimental}) - g_m(\text{dark, experimental})$$

$$(\Delta g_m)_{th} = g_m(\text{under illumination, theoretical}) - g_m(\text{dark, theoretical})$$

confirms the validity of our model.

V. Conclusion

The change in the transconductance g_m and the S-parameters of commercially GaAs MESFET's illuminated by the light of photon energy greater than the gap bandwidth is shown. We believe that this change in the dc and ac characteristics is explained by the photoconductive and photovoltaic phenomena. These effects can be applied to the design of amplifiers and oscillators driven by light and ultra-fast photodetectors.

References

[1] C. Baak, G. Elze, and G. Walf, "GaAs MESFET: A high-speed optical detector," *Electron. Lett.*, vol. 13, p. 139, 1977.
[2] J. M. Osterwaller and B. J. Rickett, "GaAs MESFET demodulates gigabit signal rates from GaALAs injection laser," *Proc. IEEE*, vol. 67, pp. 966–968, 1979.
[3] J. C. Gammel and J M. Ballantyne, "The OPFET: A new high-speed optical detector," in *Proc. IEDM*, pp. 120–123, 1978.
[4] A. J Seeds, "The optical control of avalanche diode oscillator," Ph.D. thesis, Univ. of London, 1980.
[5] A. A. de Salles and J. R. Forrest, "Initial observations of optical injection locking of GaAs metal semiconductor field effect transistor oscillators," *Appl. Phys. Lett.*, vol. 38, pp. 92–394, 1981.
[6] A. A. de Salles, "Optical control of GaAs MESFET's," *IEEE Trans. Microwave Theory Tech*, vol. MTT-31, Oct. 1983.
[7] J. Graffeuil, P. Rossel, and H. Martinot, *Electron. Lett*, vol. 15, pp 439–441, 1979.
[8] A. A de Salles, "Optical control of microwaves field effect transistors," Ph.D thesis, Univ. of London, 1982.
[9] G. J. Chaturvedi, R. K. Purohit, and B. L. Sharma, "Optical effect on GaAs MESFET's," *Infrared Phys.*, vol. 23, no. 2, pp. 65–68, 1983.
[10] H. Mizuno, "Microwave characteristics of an optically controlled GaAs MESFET," *IEEE Trans. Microwave Theory Tech*, vol. MTT-31, pp. 596–600, July 1983.
[11] J. M. Fougnon, J. L. Gautier, D. Pasquet, and P. Pouvil, "Traceur de caracteristiques," Brevet d'invention, no. 8318858, Anvar, France.
[12] J. L. Gautier, P. Pouvil, and D. Pasquet, "Calibration d'un analyseur de reseaux dans les plans de mesure d'une structure micro-ruban standard," Rapport interne E.N.S.E.A., 1984.
[13] J. P. Noad, E. H. Hara, R. H. Hum, and R. I. Macdonald, "FET photodetectors: A combined study using optical and electron-beam stimulation," *IEEE Trans. Electron Devices*, vol. ED-29, pp. 1792–1797, 1982.
[14] W Schockley, "A unipolar field effect transistor," *Proc. IRE*, vol. 40, p. 1365, 1952.
[15] D. Boccon-Gibod, "Modèle analytique et schéma équivalent du MESFET GaAs," *Acta Electron.*, vol. 23, no. 2, pp. 99–109, 1980
[16] J. G. Ruch, "Electron dynamics in short channel FET," *IEEE Trans. Electron Devices*, vol. ED-19, pp. 652–654, May 1972.
[17] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. New York: Wiley Interscience, 1981.

Complex Permittivity Instrumentation for High-Loss Liquids at Microwave Frequencies

H. A. BUCKMASTER, SENIOR MEMBER, IEEE,
C. H. HANSEN, ASSOCIATE MEMBER, IEEE, AND H. ZAGHLOUL

***Abstract* — This note draws attention to the fact that the instrumentation system for the measurement of the complex permittivity of high-loss liquids proposed by Zanforlin [1] can be improved so as to i) increase the sensitivity and stability of the demodulation process, ii) make the demodulation accurately linear rather than approximately square law, and iii) improve the degree of bridge balance and stability.**

Recently, Zanforlin [1] described a method for determining the complex permittivity of high-loss liquids at millimeter wavelengths which uses a matched hybrid-tee in a balanced bridge configuration. This configuration is a slight modification of an earlier balanced bridge due to Hallenga [2] which was developed to determine the complex permittivity of both high- and low-loss liquids by measuring the change in the Q factor and the shift in the resonant frequency of a resonant cavity. The object of this note is to draw attention to several shortcomings in this instrumentation system as well as to provide methods for their resolution. It also discusses the method of analyzing the experimental data obtained using the Zanforlin [1] cell which is an extension of that due to Van Loon and Finsy [3] and the references therein.

Manuscript received October 23, 1984; revised April 15, 1985. This work was supported in part by the Natural Sciences and Engineering Research Council and the University of Calgary.

The authors are with the Physics Department, the University of Calgary, Calgary, Alberta, Canada T2N 1N4.

0018-9480/85/0900-0822$01.00 ©1985 IEEE

It is useful to recall that balanced bridges have been used for over twenty years to measure the complex permeability of paramagnetic samples using the technique of electron paramagnetic resonance (EPR). Strandberg [4] was probably the first worker to recognize that the microwave demodulation figure of merit could be improved significantly by incorporating a synchrodyne (homodyne) [5] microwave demodulator. In EPR, the sample irradiation cell is a resonant microwave cavity (rectangular TE_{101} or TE_{102}, cylindrical TE_{111} or TE_{011}) and the sample is located where the microwave magnetic field is a maximum and is immersed in a variable external magnetic field.

The phase of the synchrodyne reference arm power determines whether the imaginary (absorption) or the real (dispersion) component of the complex permeability is demodulated. Buckmaster and Dering [6]–[10] and Dering [11],[12] explored many aspects of how to optimize EPR spectrometer stability and sensitivity using synchrodyne modulation. Many of the fundamental signal-processing concepts that they introduced into EPR spectroscopy are also applicable to complex permittivity microwave measurement instrumentation systems. Strandberg [13] has provided a comprehensive study of the effect of microwave oscillator A.M. and F.M. noise on the sensitivity of both resonant and nonresonant instrumentation systems.

Zanforlin [1] and Hallenga [2] both used a square-law detector which was followed in the former configuration by a SWR meter, and the microwave power incident on the bridge is amplitude modulated at 1 kHz using a ferrite modulator. This configuration suffers from the following weaknesses: i) low sensitivity, ii) assumes that the detector accurately satisfies a square-law characteristic, iii) low bridge balance, iv) poor bridge balance stability, and v) amplitude modulator introduces nonlinearity and phase variation. The availability of low $1/f$ noise Schottky-barrier diodes [14] intended for use in zero IF Doppler radar determines that the synchrodyne configuration is the optimum demodulator. This configuration will provide the highest sensitivity, and the demodulation is linear within 0.001 dB provided that the signal power is more than 30 dB below that of the reference power [5],[15], making it unnecessary to know the exact square-law characteristic of the demodulator as a function of the operating point, thereby eliminating a major source of error.

The matched hybrid-tee approach used by Zanforlin [1] is very difficult to reproduce but no statistical information is given on this procedure. It is estimated that the reproducible error is not better than a few percent. It has been demonstrated experimentally [8],[12] that bridge balances of 130 dB can be achieved and maintained for hours in a nonresonant bridge if a rotary vane attenuator and phase shifter are used as the bridge balancing elements and the spectral purity and stability of the microwave power source is $1:10^8$. Experience in our laboratory has led us to conclude that ferrite amplitude modulators introduce considerable amplitude and phase fluctuations which will also be an error source. The use of p-i-n diode modulation is preferrable at those frequencies where they are available since they are characterized by fast rise-times, low incidental FM, and nearly constant input and output impedance match.

Fig. 1 shows a version of the microwave instrumentation configuration used by both Zanforlin [1] and by Hallenga [2] that minimizes the abovementioned weaknesses. It has been found possible to measure the power reflected from the sample cells down to -128 dBm in good agreement with [8]. This means that the reflected power for a water sample can be measured over a sample cell length which is a factor of six greater than that possible using the Zanforlin [1] configuration if account is taken of the loss for water at 9 and 70 GHz.

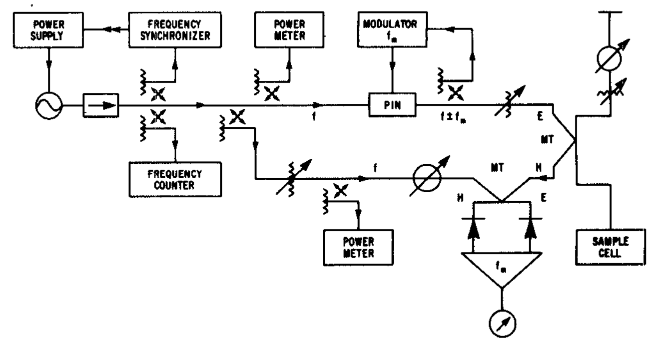

Fig. 1. Block diagram for an instrumentation system to measure the complex permittivity of high-loss liquids at microwave frequencies featuring high bridge balance and stability and high sensitivity and stability.

TABLE I

COMPARISON OF THE VALUES OF PERMITTIVITY ϵ' AND LOSS ϵ'' FOR WATER DETERMINED AT 9.3558 GHz USING DIFFERENT INSTRUMENTATION SYSTEMS.

T	20°C			25°C		
	This paper	Ref. [16]	Ref. [19]	This paper	Ref. [16]	Ref. [19]
ϵ'	61.91(43)	62.256(37)	62.426(27)	62.62(13)	64.156(38)	64.221(52)
ϵ''	32.11(32)	31.570(47)	31.575(9)	28.35(11)	28.623(43)	28.591(17)

The complex permittivity of pure water at 20 and 25°C has been determined using the microwave instrumentation configuration shown in Fig. 1. The sample cell length was adjusted in 0.001-in increments from 0.075 to 0.275 in. Two measurements sequences were necessary so that two orthogonal components could be determined. The sample bridge was balanced when the cell length was 0.075 in by adjusting the bridge rotary vane attenuator and phase shifter until the output signal was zero. This balance was tested by determining that it was independent of the synchrodyne reference arm power phase. The choice of the phase settings used for the two measurement sequences was arbitrary since it is only necessary to ensure that they are in quadrature. The reference arm phase shifter had been calibrated by McAvoy and Buckmaster [18, fig. 5] so this difference was 90.00 (25). The 201 data point pairs were fitted to the five-parameter expression for the reflection coefficient given by Van Loon and Finsy [3], which can be shown to be equivalent to the expression given by Zanforlin [1]. It is noted that Zanforlin [1] used only 18 data points to characterize this five-parameter expression and did not give the standard deviation for his fit. Table I compares the values of ϵ' and ϵ'' obtained in this work at 9.3558 GHz for water at 20 and 25°C with those reported by McAvoy and Buckmaster [16] and those made more recently in this laboratory by Zaghloul and Buckmaster [19] using an improved version of the instrument system described by McAvoy and Buckmaster [18] and used to obtain the values reported in [16]. The measurements are in agreement within experimental error. It is our assessment that the values of ϵ' and ϵ'' reported by Zanforlin [1] have errors associated with them of 2–5 percent due to the fact that only 18 data points were measured and the low signal-to-noise of these points due to the inherent sensitivity limitations of his instrument system.

Recently, McAvoy and Buckmaster [15]–[18] have developed a new 9-GHz instrumentation system to measure the complex permittivity of high-loss liquids which introduces refinements that permit ϵ' and ϵ'' to be determined to ~ 0.05 percent and ~ 0.5 percent, respectively. This is a significant advance in precision since it represents an improvement by factors of sixteen and seven, respectively [15],[16]. It is unfortunate that Zanforlin [1] failed to provide an experimental evaluation of the errors in his instrumentation system since it is a useful contribution to the methodology of complex permittivity measurements. It is concluded that the multimode nonresonant reflection cell is a useful approach, particularly at millimeter wavelengths, where the single-mode nonresonant transmission cell is difficult to realize. However, the measurement accuracy is limited to ~1 percent due to limitations in the data fitting procedure.

References

[1] L. Zanforlin, "Permittivity measurements of lossy liquids at millimeter-wave frequencies," *IEEE Trans Microwave Theory Tech.*, vol MTT-31, pp. 417–419, May 1983.

[2] K. Hallenga, "New method for very sensitive dielectric difference measurements on high-loss liquids at microwave frequencies," *Rev. Sci. Instrum.*, vol. 46, pp. 1691–1696, Dec 1975.

[3] 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, July 1975.

[4] M. W. P. Strandberg, "EMR notes from Strand labs," Strand Labs Inc, pp. 1–9, Apr. 1964.

[5] R. J. King, *Microwave Homodyne Systems.* Stevenage, Herts, England: Peter Peregrinus Ltd., 1978.

[6] H. A. Buckmaster and J. C. Dering, "Experimental sensitivity study of a 9 GHz electron paramagnetic resonance spectrometer," *Can. J. Phys.*, vol. 43, pp. 1088–1098, June 1965.

[7] H. A. Buckmaster and J. C. Dering, "The application of phase-lock microwave frequency stabilizers to electron paramagnetic resonance spectrometers," *J. Scientific Instrum.*, vol. 43, pp. 554–557, Aug. 1966.

[8] H. A. Buckmaster and J. C. Dering, "The fundamental limit to the balance of a microwave bridge containing a dispersive element," *IEEE Trans. Instrum. Meas.*, vol. IM-16, pp. 13–18, Mar. 1967.

[9] H. A. Buckmaster and J. C. Dering, "Limiting sensitivity of EPR spectrometers at high power levels," in *Proc. of the XIV Colloque Ampere* (Ljubljana), Sept. 6–11, 1966, R. Blinc, Ed. Amsterdam: North Holland, 1967, pp. 1017–1022.

[10] H. A. Buckmaster and J. C. Dering, "A 9 GHz, single-klystron, EPR spectrometer using superheterodyne demodulation," *Can J. Phys.*, vol. 45, 107–117, Jan. 1967.

[11] J. C. Dering, "Sensitivity considerations in electron paramagnetic resonance spectrometers," M.Sc. thesis, Physics Dept., Univ. of Alberta at Calgary, unpublished, 1964.

[12] J. C. Dering, "Theoretical and instrumental studies in electron paramegnetic resonance I. An investigation of the design of high-sensitivity and stability EPR spectrometer and a survey of the theory and application of generalized spin-Hamiltonian," Ph.D. thesis, Physics Dept., Univ. of Calgary, unpublished, 1967.

[13] M. W. P. Strandberg, "Sensitivity of radio frequency measurements in the presence of oscillator noise," *Rev. Sci. Instrum.*, vol. 43, pp. 307–316, Feb. 1972.

[14] For example, MA-40090 10 GHz zero IF Schottky mixer diode.

[15] J. G. McAvoy, "Two cell microwave complex permittivity measurement system," M.Sc. thesis, Physics Dept., Univ. of Calgary, unpublished, 1983.

[16] J. G. McAvoy and H. A. Buckmaster, "The 9 GHz complex permittivity of water at 293 K and 298 K," *J. Phys. D.: Appl. Phys.*, vol. 16, pp. 2519–2523, Dec. 1983.

[17] J. G. McAvoy and H. A. Buckmaster, "The 9 GHz complex permittivity of 0.001–0.05 M KCl in water at 293 K," *J. Phys. D.: Appl. Phys.*, vol. 17, pp. 2081–2085, Nov. 1984.

[18] J. G. McAvoy and H. A. Buckmaster, "A dual channel instrumentation system for precision, differential microwave complex permittivity measurements," *J. Phys. E. Sci. Instrum.*, vol. 18, pp. 244–250, Mar. 1985.

[19] H. Zaghloul and H. A. Buckmaster, "The complex permittivity of water at 9.356 GHz from 10°C to 40°C," *J. Phys. D.: Appl. Phys.*, vol. 18, 1985.

1.5-GHz GaAs Surface Acoustic Wave Delay Lines

R. T. WEBSTER, MEMBER, IEEE

Abstract —**Surface acoustic wave (SAW) delay lines fabricated on commercially available (100) cut GaAs have been used to control oscillators at frequencies as high as 1.5 GHz. These high frequencies were obtained by operating at the second overtone of transducers with three electrodes per wavelength. A theoretical and experimental study of the temperature coefficient of frequency of SAW oscillators on GaAs was performed. Tables display the GaAs elastic constants and their temperature coefficients, as well as the experimental and theoretical surface acoustic wave propagation characteristics of selected GaAs orientations.**

I. Introduction

Surface acoustic wave (SAW) delay lines fabricated on gallium arsenide have been used to control oscillators at frequencies up to 1.5 GHz. The oscillators are being developed to meet the need for stable sources on gallium arsenide monolithic microwave integrated circuits. If an oscillator is to be included on a monolithic chip, it must meet several requirements. It must be physically small; it must be compatible with the fabrication process used for the electronic circuit; its output frequency must be high to minimize the need for power-hungry multiplier chains with their associated high noise floor; it must have a useful degree of stability. These 1.5-GHz devices, the highest frequency GaAs SAW-controlled oscillators reported to date, suggest that surface acoustic wave devices can meet the requirements of MMIC applications.

II. Fabrication

Since gallium arsenide is piezoelectric as well as semiconducting, fabrication of gallium arsenide SAW devices is straightforward. Our 1.5-GHz delay lines were fabricated from commercially available polished GaAs wafers. These (100) cut wafers were semi-insulating with no intentional doping. This is the type of wafer which would typically be used for ion-implanted GaAs electronics. On the (100) GaAs surface, the surface acoustic waves propagate along the [110] direction with a velocity of 2860 M/s, an electromechanical coupling ($2\Delta V/V$) of 6.4×10^{-4}, and a zero power flow angle.

Rectangular substrates are easily cleaved from the (100) cut wafers along perpendicular {110} planes. The cleavage planes provide an excellent reference for SAW transducer alignment. "Three-Halves" (3/2) electrode interdigital transducers [1] operating at the second overtone were selected for the delay lines. The 3/2 electrode transducer employs three interdigital electrodes per wavelength at the fundamental frequency. Each electrode is 1/6 of a wavelength wide with a 1/6 wavelength space. Like the double electrode (four electrodes per wavelength, each 1/8 of a wavelength wide), it overcomes the problem of mechanical reflections in the transducer passband. At the fundamental frequency, the wider 3/2 electrodes ease the fabrication tolerances relative to the double electrode. Each transducer consists of 173 electrodes with 0.62-μm lines and spaces and an acoustic aperture of 350 μm. The transducers were photolithographically defined using the lift-off technique and a 10× direct step on the wafer exposure system [2]. Center-to-center transducer separation was 3

Manuscript received March 14, 1984; revised April 15, 1985.

The author is with the Electromagnetic Sciences Division, Rome Air Development Center, Hanscom Air Force Base, MA 01731.