Optical Effects on the Static and Dynamic Characteristics of a GaAs MESFET

J. L. GAUTIER, D. PASQUET, AND P. POUVIL

***Abstract* — In this paper, we describe the effect of light on the S-parameters of a GaAs MESFET. The photon energy is greater than the gap bandwidth of the semiconductor. The photoconductive and photovoltaic dc phenomena in the channel and in the depletion layer are theoretically analyzed with a unidimensional model to describe the light effect on the dc transconductance g_m. The comparison between the dc transconductance, without and under illumination, and the theoretical model shows a very close agreement.**

I. Introduction

The transmission of information using optical fibers requires high-speed optoelectronic detectors. Schottky-gated field effect transistors (MESFET's) have many applications in this area because they permit the design of light-driven devices [1]–[6].

Previous experimental and theoretical works have shown the light dependence of the dc and ac characteristics of MESFET's [7]–[10], but the photoconductive and photovoltaic phenomena in the channel and in the depletion layer are not theoretically analyzed.

In the present work, the effect of the light intensity on the dc transconductance g_m and the S-parameters of a commercial GaAs MESFET is shown. Then, a unidimensional model to describe the light effect on the dc transconductance g_m is considered and the behavior of the S-parameters under illumination is shown.

II. Experiment

In this experiment, the optical source is an injection laser ($\lambda = 827$ nm) which is butt-coupled to a multimode optical fiber (diameter = 500 μm). The emitted output power varies from zero up to a maximum output power of 2 mW. The distance between the fiber and the GaAs MESFET is about 1 mm.

The field effect transistor used in this work is a Hewlett-Packard HFET 5001 which has a 1.3-μm-long gate. The doping level and the thickness of the active layer constituting the channel are $N_D = 1.3 \times 10^{17}$ cm^{-3} and $H = 0.18$ μm, respectively.

This chip transistor is mounted in a microstrip fixture shown in Fig. 1. A home-made apparatus driven by a 9826 HP computer measures the static transconductance g_m [11]. The microwave measurements are performed with a network analyzer. A calibration method developed in our laboratory allows the computation of S-parameters of the MESFET at the planes P_1 and P_2 (Fig. 2) [12]. S-parameters of the MESFET have been measured between 2 and 8 GHz for several bias conditions (points A, B, C, and D) (Fig. 3).

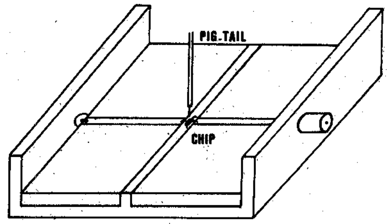

Fig. 1. Microstrip fixture.

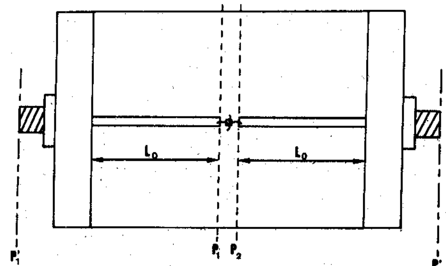

Fig. 2. Measurement planes.

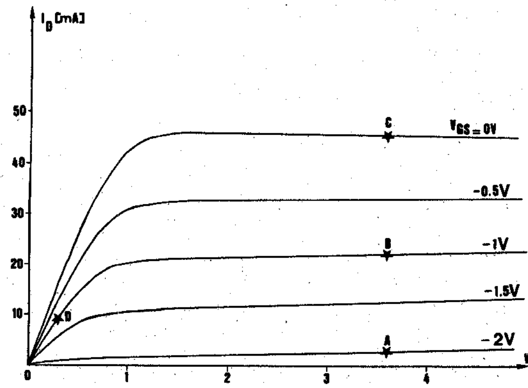

Fig. 3. Bias conditions to measure S-parameters A near the pinchoff voltage, B in the saturation region for $V_{GS} \neq 0$ V, C in the saturation region for $V_{GS} = 0$ V, and D in the ohmic region.

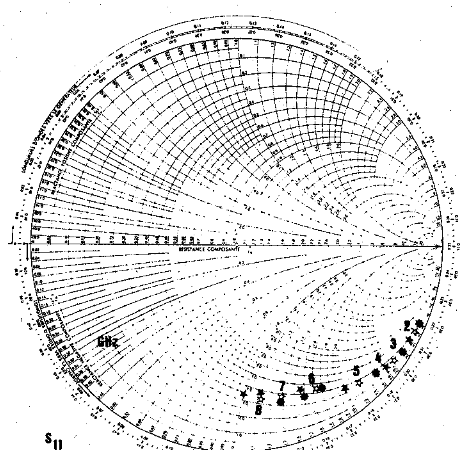

Fig. 4. S_{11} parameter at the bias point A. $*$: dark, ☆: light power = 0.3 mW, ★: light power = 2 mW.

III. Results

A. S-Parameters

For the A, B, and C bias points, the light increases the input capacitance corresponding to the parameter S_{11} (Fig. 4). The light has little effect on the parameter S_{22}. It has an important influence on the parameter S_{21} near the pinchoff (point A) (Fig. 5).

Mizuno [10] has shown that the effect of light on point A is the same as an increase of V_{GS}. A small decrease of the modulus of S_{21} is observed for $V_{GS} = 0$ (Fig. 6).

The behavior in the ohmic region (point D) is quite different. In this area, the resistance corresponding to the parameter S_{11}

Manuscript received December 11, 1984; revised April 15, 1985.
The authors are with Ecole Nationale Superieure de L'Electronique et de ses Applications, Laboratorie de Recherches, impasse des Chênes Pourpres, 95000 Cergy, France.

0018-9480/85/0900-0819$01.00 ©1985 IEEE

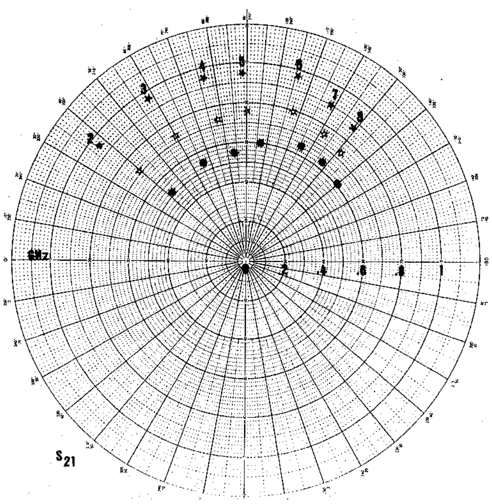

Fig. 5. S_{21} parameter at the bias point A. ∗: dark, ☆: light power = 0.3 mW, ★: light power = 2 mW.

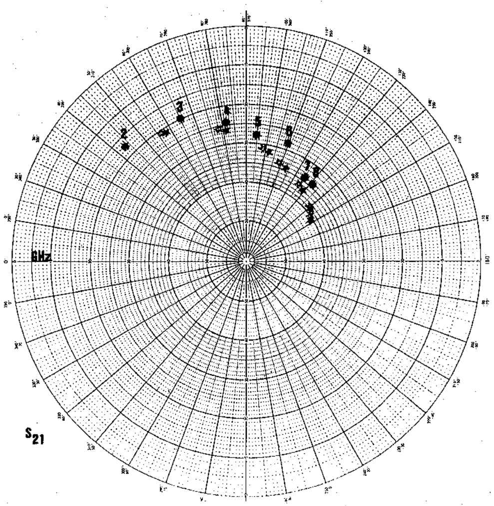

Fig. 6. S_{21} parameter at the bias point C. ∗: dark, ☆: light power = 0.3 mW, ★: light power = 2 mW.

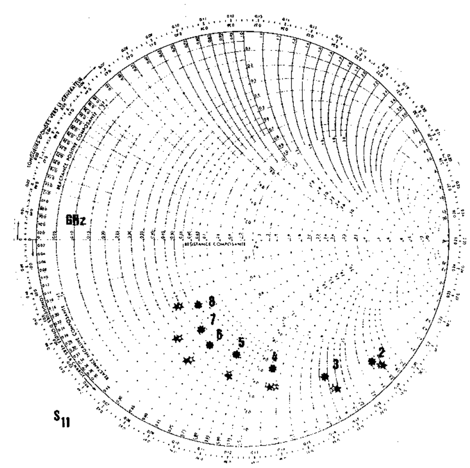

Fig. 7. S_{11} parameter at the bias point D. ∗: dark, ☆: light power = 0.3 mW, ★: light power = 2 mW.

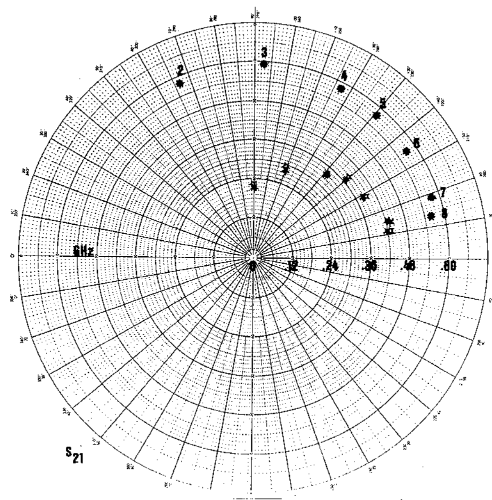

Fig. 8. S_{21} parameter at the bias point D. ∗: dark, ☆: light power = 0.3 mW, ★: light power = 2 mW.

decreases (Figs. 7 and 8). In this region, the S-parameters are relatively independent on the incident optical power level. A saturation phenomenon seems to occur with a very low light power. The light dependence of S_{12} and S_{22} parameters are less significant than the others.

B. DC Transconductance

The light has no effect on the dc transconductance g_m for V_{GS} less than -1 V. As V_{GS} increases, the light makes g_m decrease, while as V_{GS} reaches the pinchoff voltage, the light effect on g_m is inverted (Fig. 9). This result confirms the effect on S_{21} observed on the point C (Fig. 6).

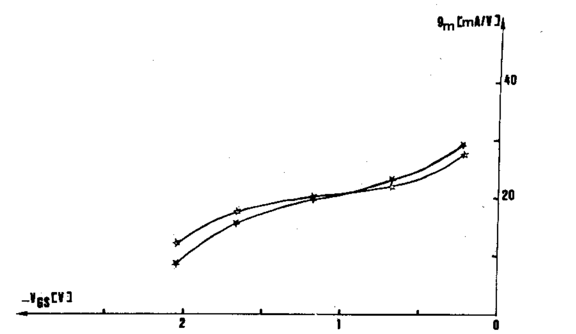

Fig. 9. Measured g_m variations versus V_{GS} for $V_{DS} = 3$ V. ★: dark, ☆: light power = 0.3 mW.

C. Reverse Gate Current

Fig. 10 shows the effect of the light on the reverse gate current. An offset voltage V_{LL} corresponding to a photovoltaic effect appears.

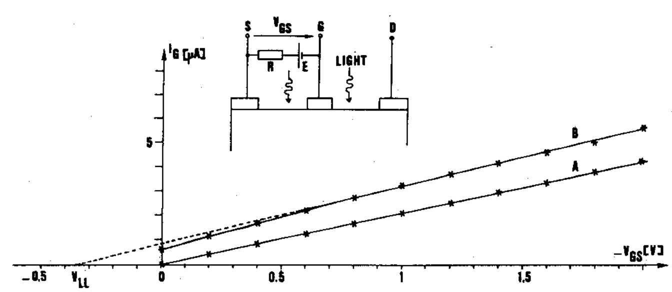

Fig. 10. Measured I_G versus V_{GS} which permits one to find V_{LL}. A: dark, B: light power = 0.3 mW.

IV. Calculation and Discussion

The effect of light on S-parameters and on the transconductance is attributed to the generation of electrons and holes which appear when the energy of the incident photons is greater than or equal to the forbidden gap bandwidth of the semiconductor [13]. A photovoltaic effect occurs in the Schottky junction of the

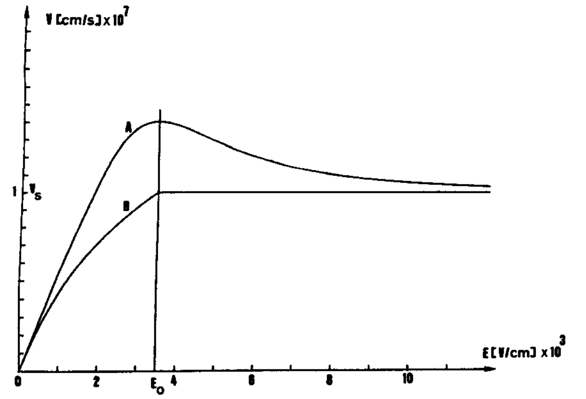

Fig. 11. Drift velocity versus electric field for GaAs. A: measured by Ruch [16], B: theory.

transistor gate, while a photoconductive effect occurs in the active region of the channel. The photovoltaic phenomenon is shown in the current–voltage characteristic (I_G versus V_{GS}) for the reverse-biased source-gate junction with open drain. Illuminating the gate has the same effect as applying a forward bias V_{LL} between the source and the gate [9] as shown in Fig. 10. The measured voltage for the optical power of 0.3 mW is $V_{LL} = 0.35$ V.

A theoretical calculation for the forward-bias voltage V_{LL} as a function of the minority carrier concentration P in the dark and of its increased value ΔP due to the creation of the electron-hole pairs under the effect of the incident light is written as follows:

$$V_{LL} = \frac{KT}{q} \ln \frac{P + \Delta P}{P} \tag{1}$$

where K is the Boltzmann's constant, T is the absolute temperature, q is the electronic charge, and ΔP depends on the absorption coefficient of the semiconductor, the transit time, the active layer width, and the number of photons falling on unit area per second.

We believe that the photoconductive effect makes the number of charges greater and, consequently, increases the value of the capacitance corresponding to the S_{11} and S_{22} parameters near the pinchoff.

Photovoltaic and photoconductive effects can be taken into account in the Schockley model [14] to describe the transconductance variation. Applying this model, we can write the drift velocity v versus the electric field E as follows [15] (Fig. 11):

$$v(E) = \frac{\mu_0 \cdot E}{1 + \dfrac{E}{E_c}}, \quad \text{for } 0 \leqslant E \leqslant E_0 \tag{2}$$

$$v(E) = v_S, \quad \text{for } E > E_0 \tag{3}$$

where μ_0 is the low-field mobility ($\mu_0 = 4500$ cm^2/V·s for $N_D = 1.3 \times 10^{17}$cm^{-3}), and where

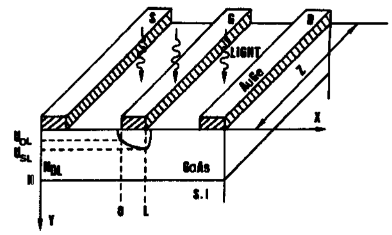

Fig. 12. Schematic cutaway of the GaAs MESFET. Gate length $L = 1.3$ μm, width $Z = 300$ μm, depth $H = 0.18$ μm.

$$E_0 = 3500 \text{ V/cm}$$

$$E_c = \frac{E_0 \cdot v_s}{\mu_0 \cdot E_0 - v_s}$$

and v_s is the saturation velocity.

For E less than E_0, we use the Schockley assumptions under the gate. For E equal to E_0, we obtain the saturation current $I_{D\,\text{sat}}$ and the electric field in the depletion region reaches to infinity.

The dark current is given by [17]

$$I_{D\,\text{sat}\,D} = I_{PD} \cdot \frac{3\left(u_{sD}^2 - u_{0D}^2\right) - 2\left(u_{sD}^3 - u_{0D}^3\right)}{1 + \dfrac{V_{PD}}{E_c \cdot L}\left(u_{sD}^2 - u_{0D}^2\right)} \tag{4}$$

where I_{PD} is the dark current near the pinchoff voltage

$$I_{PD} = q^2 \cdot N_{DD}^2 \cdot \mu_0 \cdot Z \cdot H^3 / 6\epsilon_0 \cdot \epsilon_r \cdot L \tag{5}$$

u_{0D} is the normalized depth of the depletion region for $x = 0$ in the dark for $V_{LD} = 0$ and $V_{GS} = 0$ (Fig. 12)

$$u_{0D} = \left((V_B - V_{GS} + V_{LD})/V_{PD}\right)^{1/2} \tag{6}$$

u_{sD} is the normalized depth of the depletion region for $x = L$ and $E = E_0$ in the dark with $V_{LD} = 0$

$$u_{sD} = \left((V_B - V_{GS} + V_{DS} + V_{LD})/V_{PD}\right)^{1/2} \tag{7}$$

N_{DD} is the free carrier's density in the dark, V_{PD} is the pinchoff voltage in the dark

$$V_{PD} = q \cdot N_{DD} \cdot H^2 / 2\epsilon_0 \cdot \epsilon_r \tag{8}$$

V_B is the barrier voltage of the Schottky junction ($V_B = 0.75$ V), ϵ_0 is the vacuum dielectric constant ($\epsilon_0 = 8.854 \times 10^{-14}$ F/cm), ϵ_r is the GaAs dielectric constant ($\epsilon_r = 13.1$), Z is the depth of the channel ($Z = 300$ μm), H is the thickness of the active layer ($H = 0.18$ μm), and L is the gate length ($L = 1.3$ μm).

The saturation transconductance g_{mD} in the dark is given by

$$g_{mD} = \frac{\dfrac{3LI_{PD}I_{sD}^3}{V_{PD}}(1 - u_{0D}) - \dfrac{I_{D\,\text{sat}\,D}I_{sD}^3}{E_c}}{\left[\dfrac{V_{PD} \cdot I_{sD}}{E_c} - 2I_{PD}L\right]\left[3I_{D\,\text{sat}\,D}^2 + \dfrac{3I_{D\,\text{sat}\,D} \cdot I_{sD}\left(3I_{PD}L - \dfrac{2V_{PD} \cdot I_{sD}}{E_c}\right) + I_{sD}^3\left(L + \dfrac{V_{PD}}{E_c}\left(1 - u_{0D}^2\right)\right)}{\dfrac{V_{PD} \cdot I_{sD}}{E_c} - 2I_{PD}L}\right]} \tag{9}$$

where I_{sD} is the saturation current in the dark corresponding to the maximum current which could exist without the depletion region and with carriers traveling at their saturation velocity v_s

$$I_{sD} = q \cdot N_{DD} \cdot Z \cdot H \cdot v_s. \tag{10}$$

The saturation current $I_{D\,\text{sat}\,L}$ and the transconductance g_{mL},

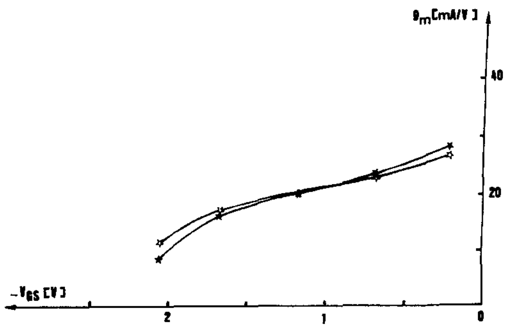

Fig. 13. Calculated g_m versus V_{GS} in the saturation region. ★: dark, ☆: light power = 0.3 mW. $N_{DD} = 1.3\times10^{17}$ cm^{-3}, $V_{LD} = 0$ V, $N_{DL} = 1.5\times10^{17}$ cm^{-3}, $V_{LL} = 0.35$ V.

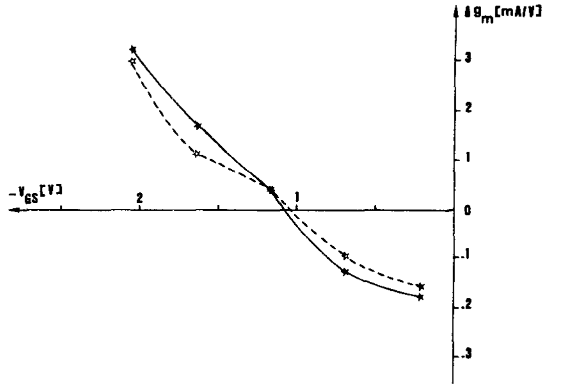

Fig. 14. ★: $(\Delta g_m)_{ex} = (g_{mL} - g_{mD})_{experimental}$ versus V_{GS} in the saturation region ☆: $(\Delta g_m)_{th} = (g_{mL} - g_{mD})_{theoretical}$ versus V_{GS} in the saturation region.

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