# Very High Sensitivity Heterodyne Detection of X-Band Radiation with Neon Indicator Lamps

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*Abstract*—**Very high sensitivity with simple inexpensive commercial neon glow lamps designed for indicator-lamp applications is observed at $X$ band in synchronous detection. Typical minimum detectable signals with 10-nW-order local-oscillator powers are $10^{-17}$ W · Hz$^{-1}$ or lower. This is equivalent to $10^{-22}$ W · Hz$^{-1}$ with 1-mW local-oscillator power. As such lamps can be used without damage in high microwave fields, they can be used in principle with appropriate local-oscillator power levels to reach ideal microwave noise equivalent power (NEP) limits. The low NEP and noise figure result from the high responsivities of such devices which are due to high internal signal gain. Experimental results correlate well with the enhanced-ionization collision-rate detection model.**

## I. Introduction

COMMERCIAL glow-discharge indicator lamps, whose individual price is ordinarily a fraction of a dollar, have been shown to exhibit excellent sensitivity, as compared to the much more expensive diode detectors, to both millimeter-wave [1], [2] and microwave [3], [4] radiation. Utilization of such devices for detection of electromagnetic radiation has been extended to the infrared [5], visible [6], [7], and ultraviolet [8], [9] spectral regions. The ability to sense fairly accurately microwave frequency with such devices has also been demonstrated [10], [11]. In addition to fine sensitivity and low price, advantages of neon indicator lamps, as compared to diodes, for detection of electromagnetic radiation include less sensitivity to ambient temperature changes [12]–[14], much greater dynamic range and electronic ruggedness, and the ability to detect sudden increases in radiation levels without being damaged [11], [13], [14]. Also, they can be used in environments such as the Van Allen belt, nuclear reactors, or space systems subject to intense ionizing radiation fields [15] where many other types of detectors cannot operate reliably.

Lamp operation as a detector is quite simple. A dc discharge is sustained in the manner shown in Fig. 1. The common, commercial indicator lamps used here are characterized by parallel-wire electrodes with very short distances ($\simeq$ 1–2 mm) between them, as can be seen in dimensional drawings shown elsewhere [1], [10]. As a result of the small interelectrode space, there is no positive column.

The lamps were biased to *abnormal* glow discharge [1], [6], [7] which, except for $1/f$ noise, are characterized by flat thermal noise spectra [7], [16] and positive dynamic resistance [7]. Although the anode in combination with the plasma can act as a rectifier [17], a new model of detection

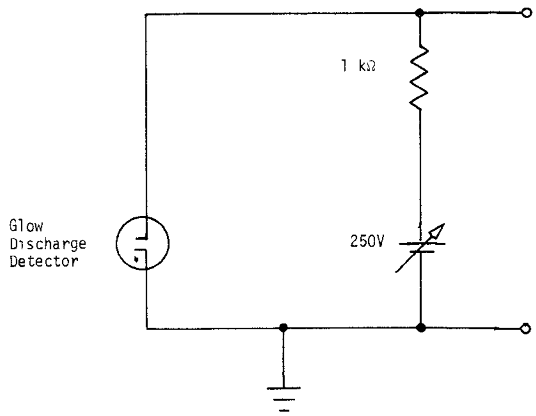


Fig 1 Glow-discharge dc bias circuit.

[11] by dc glow-discharge plasmas of microwave radiation has been suggested recently which, on the basis of extensive previous measurements of discharge parameters in such devices [1], exhibits excellent correlation with experimental results. This model takes into account the conditions under which the detected signal is manifested as either a decrease or increase in discharge current [18]. If the dc field in the plasma is sufficiently strong, increases in kinetic energy absorbed by electrons are translated into ionizing collision-rate enhancement [19], which increases the discharge current. For weak dc fields (normal or subnormal glow), microwave-field-enhanced electron energy is manifested as an enhanced diffusion current which decreases the discharge current [18], [20]. The small electrode separations in common indicator lamps allow implementation of the enhanced-ionization effect through a strong dc field (abnormal glow) with minimal losses to diffusion. These phenomena are actually small-signal effects [11] of gas breakdown by strong microwave [21], [22] or laser [23] fields without the preionization provided by dc bias. Because, at low (microamp order) discharge currents (subnormal glow) as a result of secondary electron emission, both signal and noise are dependent upon video frequency [7], [16], it is often preferable to bias the glow tube to the *abnormal* glow. In this case, the increase in discharge current as a result of enhanced-ionization microwave-signal power density $P_d$ at a radian frequency $\omega$ much larger than the plasma frequency is approximately [11], [19]

$$\Delta I_D \simeq \frac{q^2 V \eta_0 \nu n G}{m V_i(\nu^2 + \omega^2)} P_d \tag{1}$$

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where $q$ and $m$ are electron charge and mass, respectively, $\eta_0$ is the wave impedance of free space, $\nu$ is the average frequency per electron of elastic collisions with neutral atoms, $V_i$ is the ionization potential in volts of the gas mixture, $n$ is the number density of free electrons, $V$ is the plasma volume, and $G$ is the internal signal amplification by the discharge. The increase in discharge current leads to an increased potential drop across the load resistor in Fig. 1. As the resistor and glow tube are connected in series with a dc source, the discharge voltage decreases as a result of the microwave signal. For a received power $P_r$, the decrease $\Delta V_D$ in discharge voltage yields a responsivity

$$R = \frac{\Delta V_D}{P_r} \simeq \frac{q^2 d\eta_0 \nu n G Z}{m V_i(\nu^2 + \omega^2)} \quad (2)$$

where $d$ is the path length through the discharge traversed by the microwave signal and $Z$ is the discharge–load-resistance combination video-frequency impedance ($\simeq 100\ \Omega$ in such commercial devices at 10–15-mA discharge current with 1-k$\Omega$ load resistance). The internal signal gain stems from cascade effect ionizing collisions as a result of the fairly strong dc field of signal electrons with neutral atoms, i.e., each initial electron produced by microwave-field ionization enhancement can produce many additional charge carriers in ionizing collisions resulting from the dc field, and each such secondary electron can then produce additional charge carriers, etc. In common neon indicator lamps, in the abnormal glow $G$ has been shown to be on the order of $10^6$ according to the expression

$$G \simeq \frac{e^{2\nu_i t_d}}{2\nu_i t_d}$$

where $\nu_i$ is the dc ionization rate per electron and $t_d$ is the average transit time required for an electron emitted from the cathode to reach the anode [11], [20].

A separate series of experiments to be reported elsewhere indicates that the microwave circuit effect of the electrode structure in such devices appears to be minimal at $X$ band [24]. Except for dependence on $d$ as described in (2), the response of these simple, inexpensive devices is almost isotropic (directivity differences < 3 dB) with any slight differences from isotropic behavior attributed to glass-envelope curvature effects. The microwave responsivity is independent of dc-field polarization. Previous directivity measurements at $S$ band indicate again almost isotropic response provided the direction of lamp-orientation variation is such that $d$ is constant [25]. Antenna properties exhibited by electrodes [10] are found to be rather insignificant in such devices [24]. As rectification requires conversion of signal wave into current through an antenna-like effect, such phenomena do not appear too likely here. On the other hand, since ionizing collisions are dependent upon a total energy difference between colliding electron and neutral molecule, and not velocity in a given direction, response directivity results tend to support the microwave-enhanced-ionization detection model. Additional experimental verification of (2), in terms of dependence of responsivity on $\nu$, has been reported previously by Farhat [19] for tubes with such electrode geometries.

Glow-discharge detector response is seen from (1) and (2) to vary linearly with microwave signal power. This linearity holds over a wide range of signal powers and dc bias conditions [11], [14], [25]. These devices are capable, therefore, of detecting linearly two microwave signals simultaneously [2], [26], [27]. In fact, this is so even for a microwave and an optical signal simultaneously [5], [7].

The purpose of this paper is to report the high sensitivity observed in synchronous detection of $X$-band radiation by simple, inexpensive, commercial neon indicator lamps when they mix signal and local-oscillator radiation and the correlation of such results with the enhanced-ionization detection model as described by (2).

## II. Experimental System

The experimental system used for these measurements is shown in Fig. 2. The klystron which served as the signal source generated a measured signal power of 1.6 mW. The other klystron, serving as the local-oscillator source, generated 1.5 mW. In order to operate with a constant difference (IF) frequency, a phaselock loop was established between the two sources. The two reflex klystrons were tuned mechanically to operate at around 9.64 GHz. The signal source served as a VCO in the phaselock loop [28] with a function generator operating at 50 kHz which served as the difference frequency used here. The magic-T mixed the radiation from the two klystrons with the difference signal detected by a 1N23 crystal diode. The IF signal was compared with the 50-kHz function generator signal in a phase-detection circuit (RCA 4046). The output of the comparator was amplified by the isolator amplifier and changed the VCO reflector voltage and thus the frequency of the signal klystron with relation to the local-oscillator klystron in order to keep the difference frequency set at 50 kHz. Because of the high voltage-to-frequency sensitivity (2 MHz/V) of the electrical-tuning capability of the VCO klystron reflector voltage, it was necessary to stabilize its power supply by doing away with the low-pass filter normally used in such loops. This is so because a fairly stable power supply has an inherent low-pass filter, and adding an additional filter causes unnecessary stability problems. Since the high reflector voltage floats, it was necessary because of the required dc coupling to isolate it from the phase-comparator output. An optical isolator (Raytheon ISO-Lit 1) was used for this purpose.

The microwave radiation was incident directly on the glow lamps. The detected signal was amplified over a 10–100-kHz bandwidth and its rms value determined as shown in Fig. 2.

The glow lamps were situated in the far field of the transmitting horns, as shown in Fig. 2, and orientated with their electrode-plane parallel to the direction of microwave energy flow and perpendicular to the microwave electric field.

## III. Experimental Results

The measurements of noise equivalent power (NEP) and responsivity are summarized in Table I. As the detector is a

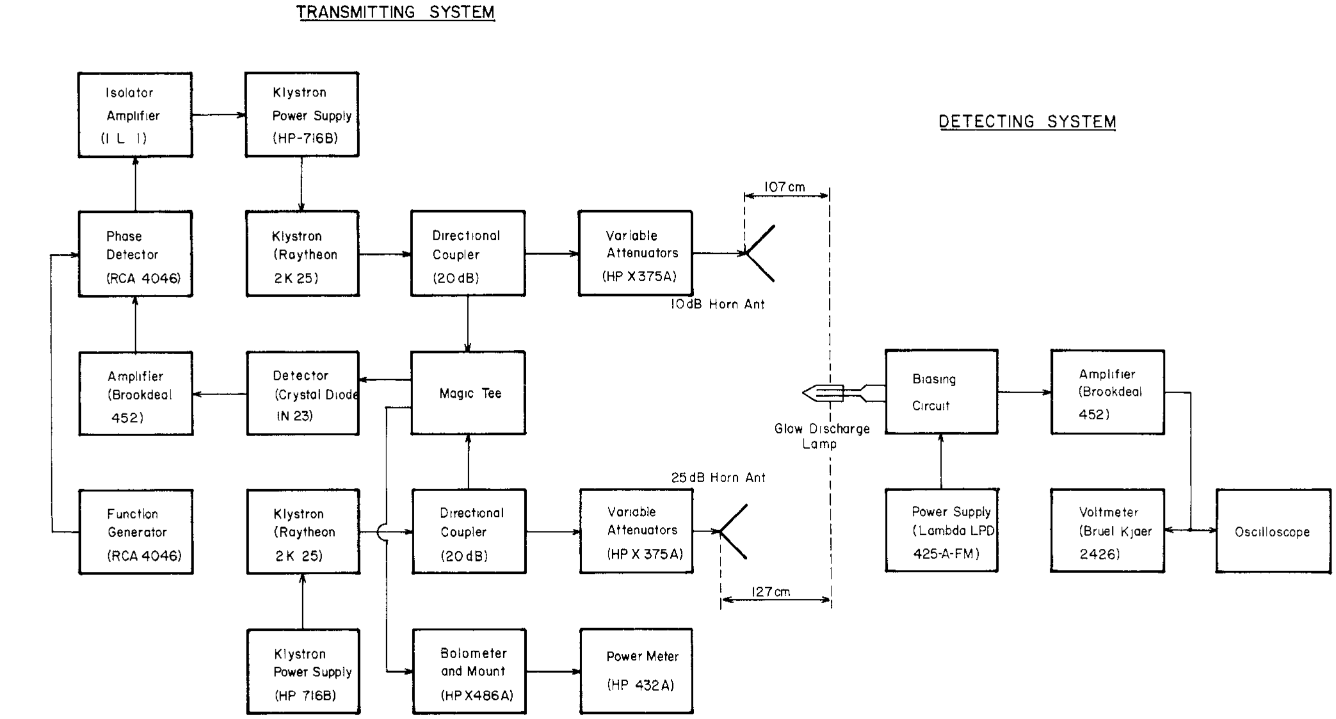


Fig. 2. Microwave experimental setup for synchronous detection measurements. Direction of microwave electric field is perpendicular to plane of paper

TABLE I
COMMERCIAL NEON GLOW-LAMP SENSITIVITIES IN SYNCHRONOUS DETECTION TO X-BAND RADIATION WITH LOCAL-OSCILLATOR POWER AS LISTED

| Tube | $I_D$(mA) | $A_r$(mm$^2$) | $V_n$($\mu$V) | $\overline{P_{LO}}$(nW) | R(V·mW$^{-1}$) | NEP (W·Hz$^{-1}$) |
|---|---|---|---|---|---|---|
| Ao-59-2 | 12 | 0.60 | 65 | 33.8 | 462 | $3.26\times10^{-18}$ |
| A-1-B | 15 | 0.44 | 85 | 8.2 | 136 | $9.05\times10^{-18}$ |
| NE-3 | 10 | 1.01 | 88 | 18.7 | 423 | $1.29\times10^{-17}$ |
| NE-51-H | 20 | 1.09 | 76 | 20.3 | 337 | $1.39\times10^{-17}$ |
| NE-76 | 4 | 1.26 | 75 | 23.4 | 288 | $1.61\times10^{-17}$ |
| NE-4 | 4 | 1.10 | 68 | 20.4 | 169 | $4.43\times10^{-17}$ |
| NE-7 | 10 | 19.63 | 81 | 365 | 31.7 | $9.96\times10^{-17}$ |

square-law device, the change in discharge current generated by the microwave energy is proportional to

$$\Delta I_D \propto [\sqrt{P_s}\cos(\omega_s t + \phi_s) + \sqrt{P_{LO}}\cos(\omega_{LO} t + \phi_{LO})]^2 \tag{3}$$

where $P_{LO}$ is the received peak local-oscillator power, $\omega_s$ and $\omega_{LO}$ are the microwave radian signal and local-oscillator frequencies, and $\phi_s$ and $\phi_{LO}$ are the corresponding phase angles, respectively. Equation (3) reduces to cosine-squared terms at frequencies $2\omega_s$ and $2\omega_{LO}$ which, because of the limited detector response time result only in dc components of $\Delta I_D$, and to sum and difference frequencies. The frequency $(\omega_s + \omega_{LO})$ is also too high for the detector to follow, thus resulting only in an IF component at the frequency $\omega_s - \omega_{LO}$ of peak magnitude $\sqrt{P_s P_{LO}}$ or $2\sqrt{\bar{P}_s \bar{P}_{LO}}$, where $\bar{P}_s$ and $\bar{P}_{LO}$ are the average signal and local-oscillator powers.

The rms value of the IF signal current is therefore a result of the received microwave IF power $P_r$ equal to $\sqrt{2\bar{P}_s \bar{P}_{LO}}$.

The heterodyne responsivity of the detector is, accordingly,

$$R = \frac{\Delta V_D(t)_{\rm rms}}{\sqrt{2\bar{P}_s \bar{P}_{LO}}}. \tag{4}$$

The rms power signal-to-noise ratio is

$$\frac{S}{N} = \frac{(\Delta V_D(t)_{\rm rms})^2}{\bar{i}_n^2} = \frac{2\bar{P}_s \bar{P}_{LO} R^2}{4\left(kT_e + \frac{2P_{dc}}{nVv}\right) BR_0} \tag{5}$$

where the denominator is the rms "thermal"-noise voltage power of the glow lamp [11], [29], which is larger than the postdetection amplifier noise. In (5) $k$ is Boltzman's constant, $T_e$ is electron temperature, $P_{dc}$ is dc power dissipation in the lamp, $B$ is the noise bandwidth, and $R_0$ is the tube dc resistance. Lamp operation in the abnormal glow, where the discharge current is relatively high, results in less noise because of decreasing $R_0$. In addition, absence of a positive column decreases noise further via electron temperature reduction [1]. Minimum detectable signal $\bar{P}_{s_{\min}}$ occurs at unity signal-to-noise ratio and results in an NEP of

$$\frac{\bar{P}_{s_{\min}}}{B} = \frac{2\left(kT_e + \frac{2P_{dc}}{nVv}\right) R_0}{\bar{P}_{LO} R^2} = \frac{\bar{i}_n^2}{2\bar{P}_{LO} R^2 B} \tag{6a}$$

or, in view of (5), a noise figure of

$$F = \frac{\overline{v_n^2}}{2\bar{P}_s\bar{P}_{LO}R^2} \Bigg/ \frac{kT_0B}{\bar{P}_s} = \frac{\overline{v_n^2}}{2\bar{P}_{LO}R^2kT_0B} = \frac{\text{NEP}}{kT_0} \quad (6b)$$

where $T_0$ is 290 K. The received-signal and local-oscillator powers were determined according to

$$P_s = \frac{P_T G_s A_r}{4\Pi R_s^2} \quad (7a)$$

$$P_{LO} = \frac{P_{TLO} G_{LO} A_r}{4\Pi R_{LO}^2} \quad (7b)$$

where $P_T$, $G_s$, and $R_s$ and $P_{TLO}$, $G_{LO}$ and $R_{LO}$ are the *measured*-signal and local-oscillator klystron powers, antenna gains, and measured receiver distances, respectively, and $A_r$ is the glow-tube detector area which was assumed to consist of the area between the electrodes. In measuring NEP, the signal-klystron radiation was attenuated with the variable attenuators until the detector noise level was reached. The signal power in (7a) divided by the appropriate attenuation and 90-kHz receiver bandwidth is the experimentally determined value of NEP shown in Table I. Measurements of detector noise levels permitted additional verification according to (6a). The values of NEP according to both methods are in very close agreement. Responsivities were determined according to (7) and (4). They are very high because of the internal signal gain. The values of responsivity here are generally about 10–100 times higher than those measured in [4]. The latter correlate well with the enhanced-ionization detection model as described by (2) [11]. The higher responsivity observed here is partly a result of a different value of $d$. In the video detection measurements [4] the parallel-wire electrodes were oriented in a plane parallel to the microwave electric field and perpendicular to the direction of microwave energy flow. This means that the value $d$ in (2) of plasma pathlength traversed by the microwave signal in [4] is equal to approximately the electrode thickness, or about 1 mm. In the measurements reported here, the value of $d$ is equal, depending on the discharge current, to almost the total electrode length, as shown in Fig. 2. Electrode lengths are on the order of 4–14 mm, depending on the glow lamp. The change in glow-lamp orientation is also reflected in the fact that in the geometric orientation used here the optimum values of discharge current are somewhat higher than those listed in [4]. In the latter measurements, $d$ was not dependent on discharge currents. In the geometric orientation used here, $d$ increases with discharge current. Thus the increase in $d$ alone here improves responsivity by roughly a factor of 10.

Another factor yielding improved responsivity here is the effect of tangential microwave electric fields on the discharge. In the previous geometrical orientation the tangential-field boundary conditions required the microwave field in the plasma to be zero on all sides along the electrode length. In the orientation used here, the tangential electric-field boundary conditions applied along the electrode thickness and only along a small differential of the electrode length. Thus, in the orientation used here, more of the plasma is available to interact with the microwave-signal electric field, and the internal signal gain is increased accordingly. Assuming then an ionization potential of neon, an electron density of $10^{16}$ m$^{-3}$, an elastic collision frequency $\nu \approx \omega$ [1], [10], [11], [19], and an internal signal gain of $10^7$ instead of $10^6$, the responsivities measured here agree reasonably well with (2).

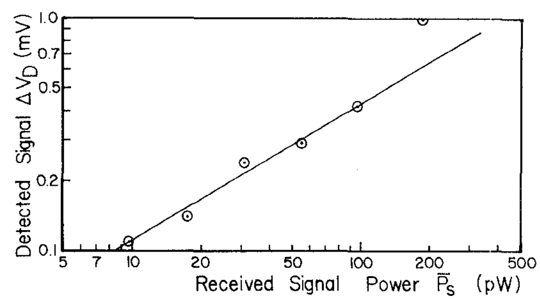


Fig. 3. Variation of neon glow-lamp detector output signal with received-signal power for Signalite Inc. AO59-2 glow lamp. Discharge current is 12 mA and received local-oscillator power is 33.8 nW.

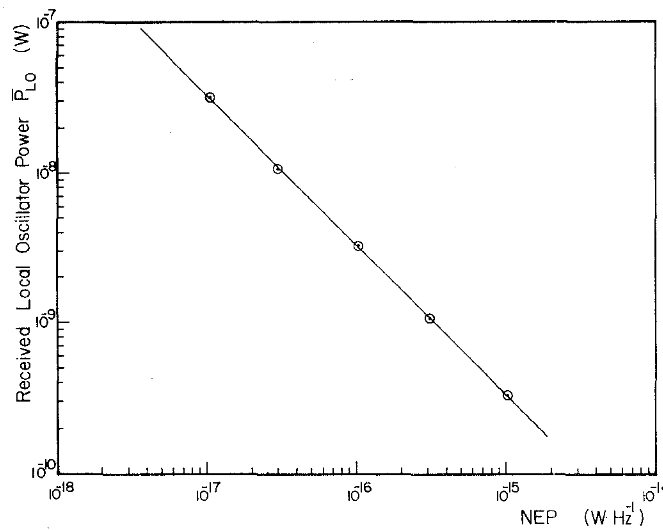


Fig. 4. Variation of AO59-2 glow-lamp NEP with received local-oscillator power. Discharge current is 10 mA. Signal power, decreased to determine NEP experimentally at each measurement, is equal approximately to 90 kHz × NEP.

The NEP values measured here are in the order of $10^{-17}$ W · Hz$^{-1}$ when the received local-oscillator power is on the order of 10 nW. This means, according to (6), that, if the received local-oscillator power were on the order of a milliwatt, the expected NEP values would be in the order of $10^{-22}$ W · Hz$^{-1}$. Experimental confirmation of the effect of received-signal and local-oscillator powers on (4) and (6), respectively, is shown in Figs. 3 and 4. Fig. 3 shows the dependence of IF responsivity for the A059-2 glow lamp on $\sqrt{\bar{P}_s}$, within the experimental limits imposed by the calibration accuracy of the Hewlett-Packard X 375A variable attenuators. Fig. 4 shows the inverse proportionality of NEP and local-oscillator power for the same glow lamp within the same experimental limits. This means, for example, that if the Signalite Corp. AO59-2 glow tube were to receive a local-oscillator power of 1 mW, its expected NEP would be

$1.10 \times 10^{-22}$ W · Hz$^{-1}$ in synchronous detection. This is equivalent to a noise-figure sensitivity limit of $1.10 \times 10^{-22}$ W · Hz$^{-1}$ ÷ ($1.38 \times 10^{-23}$ J · K$^{-1}$ × 290 K) or

$$2.75 \times 10^{-2}.$$

The thermal sensitivity of crystal diodes usually limits the local-oscillator power to an average of 10–20 mW or less because the diode is easily damaged irreversibly by incident power levels greater than about 50 mW. Glow-discharge lamps can absorb power levels many orders of magnitude higher [13], [21], [22], [25]. When the microwave-field enhancement of electron random velocity $\Delta v$ approaches the electron random velocity stemming from the dc electric field $\bar{v}$, the detector response becomes nonlinear [11]. For the argon gas AR9 tube, this nonlinearity begins at received-signal powers on the order of 200 mW [25]. However, for larger received powers, the lamp detects but the response is nonlinear. Thus, because of their electronic ruggedness and large dynamic range, glow-discharge detectors are capable, in principle, of being used with very large local-oscillator powers and thus of detecting extremely low-level signals. The output should be linear for heterodyne detection provided $\sqrt{2\bar{P}_s \bar{P}_{LO}}$ is such that $\Delta v \ll \bar{v}$. With no fear of detector damage, local-oscillator powers orders of magnitude higher than those used currently in mixers containing diode detectors can then be used to detect signal powers orders of magnitude smaller than those achievable today. The NEP sensitivity limit with glow-discharge detectors is determined thus not by detector limitations, but by natural background fluctuations of thermal emission at the frequency $\nu$ of interest. For example, at $X$ band, where $kT \gg h\nu$, $T$ being absolute temperature and $h$ being Planck's constant, the minimum detectable signal per unit bandwidth is $\varepsilon kT$, where $\varepsilon$ is the average emissivity of background objects at temperature $T$ [30]. Signals at lower power levels cannot be "seen" because of the higher natural thermal-radiation fluctuations. The ruggedness of glow-discharge detectors assures that, in principle, with appropriate local-oscillator powers these ideal NEP limits can be met. Higher local-oscillator power levels should not affect response linearity in heterodyne detection of *weak* signal as the IF component is proportional to $[2\bar{P}_s \bar{P}_{LO}]^{1/2}$. Unfortunately, equipment limitations here prevented experimental determination of NEP values with large local-oscillator powers.

Another advantage of glow-discharge detectors, in addition to those described at the beginning of this paper, is that the high sensitivity is achieved despite the high noise level as a result of the very high responsivity. This means that no special low-noise amplifiers or similar equipment is required. However, a low-ripple power supply is desirable.

Two disadvantages of commercial glow lamps should be mentioned. The diameters of the lamps are about three times the electrode separation. The sensitive detecting area is therefore a small part of the lamp cross section. Nevertheless, radiation can be focused on the plasma between the electrodes with inexpensive conducting cones from sheet metal [1] or plexiglass painted with conducting paint [26]. Such "home-made" antennas, if focused properly on the sensitive plasma volume, make much more efficient use of the lamp cross-sectional area. Another possibility is the use of tapered waveguide mounts. In addition, lamp rise times in the abnormal glow are on the order of a microsecond in commercial glow lamps [4], [1], [2], [6]. This limitation stems not from the detection mechanism itself, but from reactance inside the lamp [11] as described in (3) by $Z$. The detection mechanism itself has an inherent time constant limited by the reciprocal of the rate of relative ionization energy transfer in enhanced-ionization collisions, i.e., by the relative time lapse *between* enhanced-ionization collisions, and, as shown elsewhere [11], is less than a picosecond in these simple, inexpensive, commercial lamps. If the discharge inductance can be better understood, there is no reason why lamps cannot be designed for the purpose of being detectors, instead of indicator lamps, and the speed of response improved [31]. This is analogous to the diode detector which is limited with regard to speed of response by parasitic capacitance. As this capacitance began to be understood, better and faster detectors began to be developed.

In the experiments reported here the phaselocking was necessary because of the high klystron voltage-to-frequency sensitivity to limit the difference frequency to less than a megahertz in view of the detector rise-time limitations. No exploitation was made of the phaselocking for predetection integration. The synchronous detection here is thus equivalent to simple heterodyne detection.

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# Letters

## Comments on "Experimental Measurement of Microstrip Transistor Package Parasitic Reactances"

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In the above paper,[1] Akello *et al.* describe a method for experimental determination of the parasitics of microstrip-transistor packages, based on a resonance principle. A different method of measuring small reactances and susceptances, also permitting the determination of transistor-package elements based on time-domain techniques, is given by Piller in [1]. This method avoids the difficulties resulting from critical coaxial to microstrip transitions.

As a result, a slightly different equivalent circuit follows for a LID microwave package, as given in Fig. 1 [2], [3]. Because of the simplicity of time-domain techniques for applications up to $X$ band, this method seems to be more advantageous.

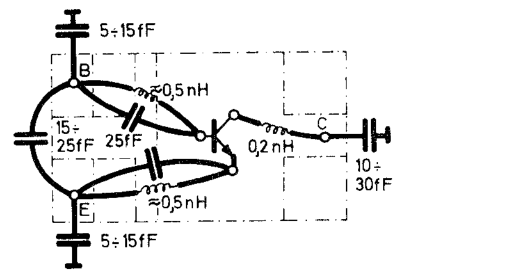


Fig. 1. LID-package equivalent circuit determined from time-domain measurements, after [2], [3].

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[1] R. J. Akello, B. Easter, and I. M. Stephenson, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 367–372, May 1977.

### References

[1] U. Piller, "Time domaine immitance measurements," in *Proc. 4th European Microwave Conf.* (Montreux, 1974), pp. 61–65.
[2] H. Beneking and E. Kohn, "$X$-band GaAs-MESFETs," presented at the European Specialist Seminar on Active Microwave Semiconductor Devices, Calvi, Corsica, November 7–9, 1973.
[3] U. Piller, "Transistor-Verbundschaltungspaare und ihre Messtechnik im Mikrowellenbereich," Ph.D. dissertation, RWTH Aachen, Aachen, Germany, 1973.