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THEORY OF A FAST, SENSITIVE, SUBMILLIMETER WAVE GLOW DISCHARGE DETECTOR

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Dimensional miniaturization and gas pressure scaling of abnormal glow discharge detectors sensitive to microwave and millimeter waves is proposed to obtain sensitive and inexpensive gas discharge detectors for submillimeter waves. Noise-equivalent-powers on the order of 10^{-13} W.Hz$^{-1/2}$ and risetimes of 14-100 ns are in principle obtainable just from scaling alone without optimization and without cooling. The high sensitivity is made possible by large internal cascade or avalanche signal gain, which permits high effective quantum efficiencies. Other advantages are low cost, electronic ruggedness, lack of sensitivity to background temperature, and very wide spectral response and dynamic range. Disadvantages are small effective receiving area and relatively high power consumption. The small receiving area may be advantageous in imaging applications.

I. Introduction

As with any frequency range of the electromagnetic spectrum, application and utilization of that wavelength interval is limited by the status of component development, availability, and expense. One of the factors limiting development and utilization of submillimeter wave systems is the status of submillimeter wave detectors. "Ideal" bolometers and 300°K "perfect" photoconductors are characterized by

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D^* values slightly greater than 10^{10}cm.Hz$^{1/2}$.W^{-1}, depending upon background temperature (Low and Hoffman, 1963). Yet uncooled bolometers and thermopiles exhibit D^* values on the order only of 10^8cm.Hz$^{1/2}$.W^{-1}. Pyroelectric detectors can yield greater sensitivity, but only at the expense of decreased response speed. Ge bolometers and InSb hot electron detectors can yield D^* values about 10^{13} cm. Hz$^{1/2}$, W^{-1} but only if cooled to liquid helium-type temperatures and operated at low information frequencies. The extreme cooling is necessary in diode devices not only to reduce thermal background but also to minimize thermal lattice vibrations which otherwise would by themselves be able to excite electrons across the forbidden energy gap because the gaps are so small for such photon energies. Often magnetic fields too are required. Superconducting detectors require not only cooling but very precise cooling, which consumes much power and is disadvantageous towards use of such detectors outside the laboratory (Richards and Greenberg, 1982). The required cooling makes utilization of the more sensitive and faster devices cumbersome and expensive. Uncooled devices result in greatly reduced sensitivity. Bolometers are limited to microsecond-order risetimes (Wilson 1983).

The purpose of this paper is to propose development of gas discharge detectors for submillimeter wavelengths. Such devices are quite inexpensive and have exhibited relatively high sensitivites to microwave (McCain, 1970, Kopeika, Galore, Stempler, and Heimenrath, 1975) and millimeter wave radiation (Severin, 1965, Severin and Van Nie, 1966, Kopeika and Farhat, 1975, Politch and Farhat, 1978, Opher, Politch and Felsteiner, 1978) in both video and heterodyne (Farhat and Kopeika, 1972, Makover, Manor, and Kopeika, 1978, Kopeika, Makover, and Schonbach, 1979) detection schemes with microsecond order risetimes. However, speed of response is limited not by the intrinsic detection mechanism (Kopeika, 1978) but by the parasitic reactance (Kopeika and Rosenbaum, 1976). Recent experiments indicate that such reactance effects should be minimized and rise time thus be improved by miniaturizing electrode geometry (Eytan and Kopeika, 1978, Zaitsev and Shaparev, 1980, and Nastase, Paseu, and Musa, 1982). That the intrinsic response speed of the discharge itself is very high is clear from the many harmonic generation and wide-band frequency-mixing operations by gas discharges at frequencies as high as the optical spectral region (Chebotayer, Klementyev, and Matyugin, 1976, Kung, Chung, and Becker, 1976, Meyer and Albach, 1976, Abrams, Yariv, and Yeh, 1977, and Abrams, Asawa, Plant, and Popa, 1977). However, the difference between the latter operations and detection is that in detection the output is an electronic voltage signal limited by reactance, rather than an electromagnetic (EM) wave. In this work, feasibility of glow discharge detection is analyzed and theoretical sensitivities and response speeds deriving from scaling down of microwave models is obtained. Room temperature noise-equivalent-power (NEP) on the order of 10^{-13} W.Hz$^{-1/2}$ and 10 ns order risetime are obtainable from such scaling. These by no means represent limits on obtainable sensitivity since discharge cells sensitive to rf energy are themselves not optimized for detection. They are manufactured as indicator lamps.

Other advantages of glow discharge detectors, in addition to low cost, include relatively little sensitivity to ambient temperature changes (Benson and Mayo, 1954, Severin, 1965, and Severin and Van Nie, 1966), large dynamic range, and electronic ruggedness. Also, they can be used in environments such as the Van Allen belt, nuclear reactors, or space systems subject to intense ionizing radiation fields (Kopeika and Kushelevsky, 1976 and Kushelevsky and Kopeika, 1976) where many other types of detectors cannot operate reliably.

Optical wave detectors exhibit signal currents I_o deriving from received power P_s described by (Oliver, 1965)

$$I_o = \frac{\eta q}{h\nu_o} G P_s \tag{1}$$

where $(P_s/h\nu_o)$ is photon rate, η is quantum efficiency, h is Boltzman's constant, ν_o is electromagnetic frequency, q is electron charge, and G is internal detector signal gain. Noise derives from shot noise (or generator-combination noise in photoconductors) and Johnson noise. As a result, signal-to-noise ratio at detector output is

$$\frac{S}{N} = \frac{\left(\frac{\eta q}{h\nu_o} G\right)^2 P_s^2}{2qB\left[\frac{\eta q}{h\nu}(P_s + P_b) + i_d\right]G^2 + \frac{4k\,T_n B}{R_L}} \tag{2}$$

where P_b is background EM wave power, B is electrical bandwidth, I_d is detector dark current, T_n is noise temperature, k is Boltzman's constant, and R_L is detector load resistor.

The terms to the left and right in the denominator in (2) represent shot and Johnson noise respectively and describe fluctuations in detector current. As such, (2) is appropriate for modulated or chopped signals.

At submillimeter wave frequencies the shot noise term is usually dominated by the background thermal emission. Hence, receiver sensitivity for low signal levels is very much subject to thermal background temperature, including that of the receiver itself.

Glow discharge detectors in the abnormal bias mode also exhibit shot and Johnson noise. However, for reasons discussed below, a version of (2) appropriate for abnormal glow discharges is

$$\left(\frac{S}{N}\right)_{GDD} = \frac{\left(\frac{\eta q}{h\nu_o} G\right)^2 P_s^{\,2} R^2}{2qB\, i_d R^2 \gamma G^2 + 4kT_e BR_o} \approx \frac{\left(\frac{\eta q}{h\nu_o} G\right)^2 P_s^{\,2} R^2}{4kT_e BR_o} \quad (3)$$

where R is discharge dynamic resistance, R_o is discharge dc resistance, T_e is electron temperature, and γ is a number much less than unity describing shot noise dampening. It is worthwhile noting that (3) implies glow discharge detectors are usually immune to thermal background because of their own high internal noise temperature. However, while submillimeter wave detectors are usually characterized by $G \simeq 1$, glow discharge detectors exhibit high internal gain on the order of 10^6 (Kopeika, 1978). Consequently, sensitive detection without external cooling and without background thermal effects is possible.

II. Analysis of Signal Power

Although many different detection mechanisms such as reduced recombination rate (Chen, Leiby, and Goldstein, 1961), enhanced diffusion (Lobov, 1960), reduced ionization potential (Severin, 1965), and rectification by the plasma-electrode interface (Anderson, 1960) have been proposed in the past and shown to play some role in the detection processes, the mechanism which appears to yield greatest responsivity is enhanced ionization (Kopeika, 1978). Since these mechanisms have been compared in the latter references, that discussion is not repeated here. The concept of enhanced ionization is essentially that of breakdown enhancement.

It is well known that high intensity electromagnetic radiation even without voltage bias to a discharge can break down the gas. It is also well known that as initial electron population or preionization level increases, the EM power density threshold required to break down the gas decreases (Smith and Haught, 1968). This has been observed in charge collection experiments involving "heating" of gases at biases below breakdown with visible (Young and Hercher,1967) and infrared (Tulip and Seguin, 1973) radiation. In the concept of enhanced ionization, the effect of the incident EM wave is to increase the breakdown beyond that produced by the high "preionization" dc bias breakdown. As such, properties and mechanisms of gas discharge detection are similar to those of gas breakdown. At long wavelengths high intensity EM wave gas breakdown is attributed to cascade type ionizing collision processes stemming from the high EM wave electric fields (Macdonald, 1966). Breakdown intensity threshold for this process increases with EM frequency since electrons have less time to achieve kinetic energies equal to ionization energies before the electric field reverses direction. At short wavelengths high intensity laser breakdown of gases is usually attributed to multiphoton ionization (Agostini, Barjot, Mainfray, Manus and Thebault, 1970, Shkarofsky, 1974, Morgan, 1975). Since, as wavelength decreases, ionization energies can be achieved with fewer photons, at visible and ultra violet wavelengths the threshold required for gas breakdown decreases with decreasing wavelength. The threshold required for gas breakdown is maximum generally in the near infrared, depending upon gas pressure and ionization potential. This is the spectral region where both the cascade ionization and the multiphon ionization mechanisms interact (Buscher, Tomlinson, and Damon, 1965, Alcock, De Michelis, and Richardson, 1969, and Morgan, Evans, and Morgan, 1971).

The spectral dependence of the gas discharge response to incident EM waves is quite similar to that of gas breakdown. Least response is in the near infrared, where gas breakdown threshold by incident EM waves is maximum (Kopeika, Eytan, and Kushelevsky, 1979, and Kopeika, 1978). Submillimeter wavelengths are long relative to the near infrared, and thus the detection mechanism of interest here is enhanced cascade type ionizing collisions. The mathematical model is developed in detail elsewhere (Kopeika, 1978). However, highlights are summarized here.

The average rate of random kinetic energy density gain under steady state conditions for $\omega_p << \omega$ is

$$\frac{d\Delta u}{dt} = \frac{\omega_p{}^2 \, \nu \, P_D}{c(\nu^2 + \omega^2)} \qquad (4)$$

where ω_p, ω, and ν are plasma, electromagnetic, and elastic electron-neutral atom collision frequencies, respectively, c is the speed of light, and P_D is average power density of the incident EM wave signal. Spectral dependence in (4) is such that maximum absorption occurs at the frequency $\omega = \nu$. If ν_i is the ionization collision rate, the ionization rate enhancement resulting from the kinetic energy $\Delta\varepsilon$ absorbed by electrons from the EM wave is (Kopeika, 1978)

$$\Delta\nu_i = \frac{\nu_i \, \varepsilon_i \, \Delta\varepsilon}{(\bar{\varepsilon})^2} \qquad (5)$$

where ε_i is atomic ionization energy and $\bar{\varepsilon}$ is average electron energy. For Maxwellian electron energy distributions this ionizing collision rate enhancement $\Delta\nu_i$ is maximum when biasing is such that $\bar{\varepsilon} \approx 0.69\ \varepsilon_i$ (Kopeika, 1978). For rare gases where ionization potential is relatively high, it is quite difficult in practice to achieve such high average electron energies. For example, in abnormal glow discharges which exhibited high responsivity to millimeter waves, $\bar{\varepsilon}$ was only about 0.4 eV (Kopeika and Farhat, 1975). This is less than 0.02 ε_i for Ne. Nevertheless, sensitivity was nearly as good as that of point contact diode detectors for 70 GHz radiation.

The EM wave induced electron energy enhancement is related to incident EM power, as a function of time t, via (Kopeika, 1978)

$$\Delta\varepsilon(t) = \frac{\tau \, q^2 \, \eta_o \, \nu \, P_D}{m(\nu^2 + \omega^2)} \left(1 - e^{-t/\tau}\right) \qquad (6)$$

where m is electron mass, η_o is free space wave impedance, and for efficient detection τ is $(\bar{\varepsilon}/\varepsilon_i)^2/\nu_i$. Ideal speed of response is limited by relative time interval between enhanced ionization collisions. Each signal electron produced via ionization collision rate enhnacement is propelled by the strong abnormal glow dc field, and produces additional electrons in cascade or avalanche signal collision processes. This results in an internal signal electron multiplication gain of (Kopeika, 1978)

$$G \approx (\exp 2\nu_i t_d)/2\nu_i t_d \tag{7}$$

where t_d is the average electron transit time required to travel from cathode to anode. In the aforementioned experiments at 70 GHz, tube properties were such that $\nu_i t_d \approx 8.5$ on the average and $G \simeq 10^6$. Over a discharge volume V, the detected discharge current increase is

$$\Delta I = I_o = qVn\, \Delta\nu_i(t)\, G \approx \frac{q^2 Vn}{V_i m} \eta_o P_D \left(\frac{\nu}{\nu^2 + \omega^2}\right)(1 - e^{-t/\tau})G \tag{8}$$

where n is electron concentration. The discharge voltage change as a result of current increase ΔI is, in the frequency domain s,

$$\Delta V(s) = \Delta I(s)\cdot Z(s) \tag{9}$$

where $Z_{(s)}$ is equivalent impedance of the discharge in parallel with load resistor R_L. In the microwave cases reactance was such that (Kopeika,1978)

$$\Delta V(t) \approx \frac{R\, q^2\, nd}{V_i\, m} \eta_o P_s \left(\frac{\nu}{\nu^2 + \omega^2}\right)\left(1 - e^{-\frac{R}{2L}t}\right) G \tag{10}$$

where d is distance through the discharge traversed by the EM field, R is discharge dynamic resistance and L is discharge inductance. The time response of the detector is determined by the energy rate of glow discharge equivalent impedance, as is the case with diode detectors. In common glow discharge lamps which exhibited good responsivity to microwave and millimeter wave radiation, measurements in the abnormal glow indicated that (Kopeika and Rosenbaum, 1976)

$$\frac{1}{R_L C} \ll \frac{R}{L} \tag{11}$$

and electronic bandwidth was

$$B = \frac{1}{2\pi}\left(\frac{1}{R_L C} + \frac{R}{L}\right) \approx \frac{R}{2\pi\, L} \propto \frac{T}{b}\frac{E}{p} \tag{12}$$

where C is discharge capacitance, T and p are gas temperature and pressure respectively, E is discharge internal electric field, and b is electrode separation. The last result indicates miniaturization and proper pressure scaling should lead to improved risetime. As b is decreased, in order for voltage dependence to remain essentially unchanged, pressure should be correspondingly increased so that bp remains constant (Paschen's law). This means that for the same voltage bias, E is considerably increased, thus improving response speed. The bias dependence of reactance is such that as current increases in the abnormal glow R and L decrease while C increases.

Equation (10) indicates that maximum responsivity is obtained at the electromagnetic frequency $\omega = \nu$. In order to obtain good responsivity at submillimeter wavelengths, it is necessary to increase electron-neutral atom elastic collision frequency and bring it into the submillimeter wave range. This requires, essentially, a corresponding increase in pressure. At 70 GHz, 100 - 200 torr Ne is a pressure range compatible with $\nu = \omega$ (Kopeika and Farhat, 1975). An order of magnitude change in EM frequency implies an order of magnitude increase in pressure to about $1\frac{1}{2}$ atm. is desirable. Paschen's law suggests an order of magnitude decrease in electrode separations from 0.5 mm to about 50 μm should be obtained. As can be seen from (12) such miniaturization should also result in improved detector risetime by an order of magnitude to about 100 ns. At such pressures it may be worthwhile to use UV, x-ray, or radioactive additive preionization techniques in order to obtain uniform discharges and prevent arc formation, as is done with TEA lasers successfully. Nevertheless, there is no reason to prevent rather uniform discharges from being obtained, particularly with such small electrode separations.

The sensitive glow discharge detectors (Kopeika and Farhat, 1975) contained 1 cm long parallel-wire cylindrical electrodes of 1 mm diameter each and 0.5 mm electrode separation. Hence, scaling proposed here involves a pair of 1 cm long parallel-wire electrodes of 100 μm diameter each and 50 μm separation, with an order of magnitude increase in gas pressure. If the same order of magnitude discharge currents are maintained (≈ 10 mA), the internal field E is increased by one order of magnitude and the electron concentration also by an order of magnitude (Guentzler, 1975). The effective field (E/p), however, remains constant. This means average electron velocity and kinetic energy and electron temperature also remain constant and have the same values as in indicator lamps sensitive to rf radiation. Although electron transit time t_d should decrease an order of magnitude because of miniaturization, the gas pressure should increase the ionization rate ν_i by the same factor, so that the product $\nu_i t_d$ and therefore internal gain remains constant. The existence of the same order of magnitude discharge current at submillimeter wave frequencies (≈ 10 mA) as that at rf frequencies, but in a miniaturized inter-electrode space, implies an order of magnitude increase in current density and in electron density, since electron velocity remains unchanged (Guentzler, 1975).

If scaling is from X-band detectors to the middle of the submillimeter wave range, scaling should be by a factor of 60 and electrode diameter and separation should be about 35 μm. Wires from tungsten and molybdenum of such thickness are readily available. Risetime, in view of (12), can be on the order of 14 ns. In all cases the gas is not pure but Penning mixtures, usually of Ne or Ar.

If pressure is increased with EM frequency so that the condition $\nu = \omega$ is obtained <u>without</u> miniaturization, the fall-off of responsivity with increasing EM frequency should be as ω^{-1}. This means that since responsivities $\Delta V/P_S$ greater than 4.5 $V \cdot mW^{-1}$ are obtained at 10 GHz (Kopeika, Galore, Stempler, and Heimenrath, 1975), then responsivities greater than 75 $V \cdot W^{-1}$ are obtainable at 600 GHz, assuming other parameters are held constant. However, the increased pressure and the miniaturization should lead to a factor of sixty increase in electron density. Therefore, responsivities greater than 4.5 $V \cdot mW^{-1}$ should be also obtainable for submillimeter waves under such conditions. To translate this into terms used for optical detectors, comparison of (1) and (8) permits determination of glow discharge detector quantum efficiency

$$\eta = \frac{hndq\eta_o}{2\pi m V_i}\left(\frac{\nu\omega}{\nu^2 + \omega^2}\right). \qquad (13)$$

If $\nu = \omega$ and $V_i \approx 21.5$ V (for Ne), then $\eta \approx 10^{-21}$ <u>nd</u>. For comparison with other submillimeter wave detectors, the internal gain should be considered and <u>effective</u> quantum efficiency $\eta \approx 10^{-21}$ <u>nd G</u>. Assuming <u>G</u> is maintained at 10^6, then $\eta_{eff} \approx 10^{-15}$ <u>nd</u>. In lamps shown to be sensitive to 70 GHz radiation, electron concentration <u>n</u> $\approx 10^{16}$ m^{-3} (Kopeika and Farhat, 1975). If signal path length <u>d</u> through the discharge is maintained at 1 cm for scaling to ~ 600 GHz, electron concentration increases to 10^{17} m^{-3} and $\eta_{eff} \approx 1$. It is clear that substantial responsivity improvement depends upon increasing the electron density. The greater the electron concentration the greater the EM wave absorption by the discharge. This principle is in accordance with the known result that gas breakdown threshold decreases with increasing preionization level. The dc electron density <u>n</u> represents "preionization" for breakdown enhancement by the incident EM wave.

It should be pointed out that the high sensitivites obtained at microwave and millimeter wave frequencies were with commercial indicator lamps designed to be indicator lamps and not optimized for efficient rf detection. The responsivities and quantum efficiencies cited here are the result only of scaling down the same parameters found to be successful at rf to be used at submillimeter wave frequencies.

III. Analysis of Noise Power

Shot noise phenomena are well known in optical detectors. However, the shot noise dampening, γ, in (2) is unique to space charge limited potential minima (Davenport and Root, 1958) as occur in electron tubes (Birdsall and Bridges, 1966). The high space charge sheath surrounding the cathode effectively smooths out fluctuations in electron emission from the cathode as seen by the anode. This applies also to signals emanating from the cathode, as with photoelectron emitters. However, in abnormal glow discharge detection the signal is detected by the discharge and not the cathode. Hence, the dampening factor γ applies to the shot noise only and not to the signal (Kopeika, 1978). It is worthwhile to consider the relative values of thermal background power ($\frac{\eta q}{h\nu} P_b$) and bias current i_d in (2). The latter is generally at 10 mA order in commercial indicator lamps that are quite sensitive to 10 GHz (Kopeika and Farhat, 1975) radiation. The scaling used here is designed to keep the current constant. Thus, i_d is assumed to be about 10 mA. Received blackbody background power is (Kopeika and Bordogna, 1970)

$$P_{bb} = \frac{2\, hc^2\, \Omega_s\, A_r\, \tau_a\, \tau_o\, \Delta\lambda}{\lambda^5\, (e^{hc/\lambda kT} - 1)} \qquad (14)$$

where T is blackbody temperature, k is Planck's constant, λ is EM wavelength, A_r is detector receiving area, Ω_s is receiver solid angle field of view, $\Delta\lambda$ is receiver spectral width, and τ_a and τ_o are atmospheric and optics transmission coefficients, respectively. Assuming these coefficients are approximately unity, that receiver field of view is 2π sr, and that at submillimeter wavelengths $hc \ll \lambda kT$, then (14) reduces to

$$P_{bb} = \frac{4\pi\, hc^2\, A_r\, \Delta\lambda}{\lambda^5 (\frac{hc}{\lambda kT})} = \frac{4\pi\, \nu\, A_r\, kT}{\lambda^3}\, \Delta\lambda. \qquad (15)$$

Since $|\Delta\lambda| = \frac{\Delta\nu\lambda}{\nu}$, (15) becomes

$$P_{bb} = \frac{4\pi\ A_r\ k_T\ \Delta\nu}{\lambda^2} . \tag{16}$$

If no spectral filters are used, $\Delta\nu$ is determined effectively by the frequency separation required for responsivity to decrease to 50% of its maximum value at $\omega = \omega_o = \nu$. Let the radian frequency of maximum responsivity be $\omega_o = \nu$. From (10)

$$\frac{\nu}{\nu^2 + \omega^2} = \frac{\omega_o}{\omega_o^{\ 2} + \omega^2} = \frac{1}{2}\left(\frac{\omega_o}{\omega_o^{\ 2} + \omega_o^{\ 2}}\right) = \frac{1}{4\omega_o} . \tag{17}$$

This leads to the result that frequency at which responsivity is reduced to 50% of its value at ω_o is

$$\omega = \pm \sqrt{3}\ \omega_o . \tag{18}$$

Since $\sqrt{3} > 1$, this means the effective spectral width of detection is very wide and is from around ω_p to $\omega_o + \sqrt{3}\ \omega_o$. Therefore, $\Delta\nu$ in (15) is $\approx (1 + \sqrt{3})\nu_o$. Let us assume ν_o = 600 GHz, λ = 0.5 mm, $\Delta\nu$ = 1050 GHz, $\underline{A_r}$ = 0.05 mm × 0.1 mm = 0.005 mm^2, and $\underline{T}$ = Te = 3300°K. The latter is average electron temperature prior to scaling (Kopeika and Farhat, 1975). (Since electron velocity is determined by E/P, electron temperature remains constant as the miniaturization increase in $\underline{E}$ is cancelled by the increased gas pressure (Guentzler, 1975). Using these values, (15) yields an unmodulated background thermal power of 1.1×10^{-9}W. Expected voltage responsivity at frequency $\nu = \nu_o$ is $4.5 V \cdot mW^{-1}$ as shown in the previous section. Assuming dynamic resistance remains constant at ≈ 100 Ω despite scaling (since scaling is designed to keep voltage-current characteristics constant), the current responsivity at this frequency is 15 $mA \cdot mW^{-1}$. Even assuming this constant throughout the effective spectral band, background current deriving from thermal background power is only about 16 nA, which is about six order of magnitude less than $\underline{i_d}$ in (2). Thus, thermal background even of the discharge itself has negligible effect.

It now remains to evaluate the relative effects of the shot noise vs. Johnson noise components in (2). Because of the shot noise dampening, the latter is usually the dominant noise source. Shot noise increases with current. The opposite is true for the abnormal glow discharge, at least until arcing sets in. Hence, the shot noise dampening is quite severe and the Johnson noise is dominant in the abnormal glow discharge.

The Johnson noise derives from random fluctuations in electron arrival rate at the anode as a result of collisions. It is characterized by electron temperature T_e and the average power dissipated P_{dc} in the tube. For a dc discharge the noise power in the frequency interval is (Parzen and Goldstein, 1951)

$$P_{NF} = \left[kT_e + \frac{P_{dc}}{N\nu} \left(2 + \frac{\nu^2 - \omega^2}{\nu^2 + \omega^2}\right) \right] B \tag{19}$$

where $kT_e = \bar{\varepsilon}$ and N is the total number of free elctrons. Many experimenters have shown a strong correlation between discharge noise and electron temperature, as compared previously (Kopeika and Farhat, 1975), which occurs when the second term in (19) is small. If the ac power dissipation is small, the noise voltage is (Severin, 1965)

$$V_n = \left[4\ kT_e + \frac{2P_{dc}}{N\nu}) B\ R_o \right]^{1/2} \tag{20}$$

where R_o is tube dc resistance. Assuming I-V characteristics do not change with scaling so that $P_{dc} \simeq (100V)(10\ mA) = 1\ W$, $N \simeq (10^{17}\ m^{-3})(10^{-2} m)(5 \times 10^{-9} m^2) = 5 \times 10^6$, and $\nu = 2\pi(6 \times 10^{11})$, it can be seen from (20) that $4kTe$ is about three times the size of $(2\ P_{dc}/N\nu)$. Hence,

$$V_n \simeq (4\ kT_e\ B\ R_o)^{1/2}. \tag{21}$$

For a 90 kHz electronic bandwidth, and $R_o \simeq 100V/10mA \simeq 10\ k\Omega$, $V_n = 9\mu V$. This agrees well with noise voltage measurements for such bandwidth (Kopeika, Galore, Stempler, Heimenrath, 1975).

With proper miniaturization and pressure scaling, this should be the noise level at submillimeter wavelengths too since I-V characteristics and electron energy remain the same.

IV. Over-all detector sensitivity

Over-all signal-to-noise power ratio at the detector output is described by (3), where quantum efficiency has been defined in (13). From (3), NEP is determined as

$$\text{NEP} = \frac{2h\nu_o}{\eta q G R}(k\ T_e\ R_o)^{1/2} = \frac{2h\nu_o}{\eta_{eff} q\cdot R}(k\ T_e\ R_o)^{1/2}. \qquad (22)$$

At 600 GHz frequency, for example, using the effective quantum efficiency calculated here ($\eta_{eff} = 1$), tube dynamic and dc resistances and electron temperature as measured in the microwave and millimeter wave cases, NEP $\simeq 1.8 \times 10^{-13}$ $W\cdot Hz^{-1/2}$. It is tempting to divide the square root of the detecting area ($A_r \approx 5 \times 10^{-3}$ $mm^2 = 5 \times 10^{-5}$ cm^2) by the NEP in order to arrive at the appropriate value of D^* without refrigeration, which turns out to be 4×10^{10} $cm\cdot Hz^{1/2}\cdot W^{-1}$. This value of D^* is two orders of magnitude better than that of any commercially available uncooled detector. Use of D^* to determine detector sensitivity would be misleading for the abnormal glow discharge, however, since D^* is a valid criterion only when detector performance is limited by thermal background shot noise, which, indeed, does depend upon $A_r^{1/2}$. Such noise, however, is irrelevant for the glow tube detector as shown above. Hence, NEP is a more valid criterion. As such, minimum detectable signal power should be competitive even with that of much more expensive cooled detectors. The very broad spectral range, lack of sensitivity to background temperature and 14-100 ns risetime are other advantages in addition to the lack of necessity for cooling.

Major disadvantages of the detector suggested here are its large power consumption (almost one watt) and its small receiving area. The latter, however, can be compensated for through use of antennas, such as conical conductors (Kopeika and Farhat, 1975) to focus the incident radiation. In addition, single detector gas cells can be made with arrays of such electrode pairs connected in series so as to work as a single detector. This would increase A_r considerably.

Alternatively, the output electrode pairs in such an array can be sampled individually and thus be used for imaging. In this case, the power consumption can be considerably less than N_a watts, where N_a is the number of electrode pairs enclosed in the gas cell. The reason is that a single cathode can be used with anodes on each side. Under such conditions, only one anode need be biased. The other floats at an internal plasma potential almost equal to that of the externally biased anode but with no current (Kopeika and Farhat, 1975). In principle, every other anode in the array can be without external bias, thus reducing power consumption and noise considerably.

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