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IF Conversion Gain of Glow Discharge Lamps as *X*-Band Mixers for High LO Power Levels

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***Abstract*—Inexpensive glow discharge indicator lamps mounted in a waveguide mount are investigated as mixers at relatively high *X*-band local oscillator (LO) power levels. The IF conversion efficiency was found to drop off for LO power levels greater than about 30–40 mW, although no damage occurs to the lamps at higher power levels. Because of the small lamp size relative to waveguide cross section, sensitivity is much less than in the free space configuration. For many reasons the use of such devices as mixers should be much more promising at millimeter-wave frequencies than at microwave frequencies.**

I. Introduction

COMMERCIAL glow discharge indicator lamps, whose individual price is ordinarily a fraction of a dollar, have been shown to exhibit rather good sensitivity to both millimeter-wave [1], [2] and microwave [3]–[5] radiation as video detectors. Utilization of this type of device for detection of electromagnetic radiation has been extended to the infrared [6], [7], visible [8]–[13], and ultraviolet [14], [15] spectral regions. The ability to sense microwave frequency with such devices has also been demonstrated [16], [17]. Other advantages of gas discharges as detectors of electromagnetic radiation include less sensitivity to ambient temperature changes [18]–[20], large dynamic range and electronic ruggedness, wide-band RF response [1], [17]–[20], and the ability to detect sudden increases in radiation levels without being damaged [17], [19], [20]. Also, they can be used in environments such as the Van Allen belt, nuclear reactors, or space systems subject to intense ionizing radiation fields [21], [22] where many other types of detectors cannot operate reliably.

The chief disadvantage is a relatively slow response (≈ 1-μs rise time). However, the rise time is limited, not by the intrinsic detection mechanism [17], [23], but by the parasitic reactance [9]. Recent experiments indicate that such reactance effects might be minimized and rise time thus improved by miniaturizing the electrode geometry [23]. The very high intrinsic speed of response by the gas discharge *itself* is clear from the many harmonic generation and wide-band frequency-mixing operations that have been observed at frequencies as high as the optical spectral region [24]–[28]. However, as in such experiments the output is an electromagnetic wave rather than an electronic voltage signal, reactance has no effect [23].

Recent experiments have indicated the feasibility of using simple inexpensive glow discharge indicator lamps as mixers at millimeter-wave [29] and microwave [30] frequencies. In particular, one suggested advantage of such an application, in addition to low price, is to exploit the wide dynamic range of these devices by illuminating them with relatively high local oscillator (LO) power levels P_{LO} so as to make possible detection of very weak signal power levels P_S [30]. This is possible in principle because the IF signal is proportional to $(P_S P_{LO})^{1/2}$. Thus as long as the product of P_S and P_{LO} does not vary much, high LO levels may in theory compensate for weak signal levels. That varying one IF component is equivalent to varying the other has been verified for low signal and LO components [30]. The purpose of this paper is to report sensitivity limitations observed at higher *X*-band power levels with inexpensive commercial indicator lamps in

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waveguide detector mounts. These experiments indicate an upper limit for RF power levels for optimum conversion efficiency.

II. Experiment

The purpose of these experiments was to determine the mixing capability of commercial glow discharge lamps when illuminated by relatively high LO power levels. The experimental setup is shown in Fig. 1. The microwave frequency was 8.69 GHz. The difference or intermediate frequency was 74 kHz.

The test system shown in Fig. 1 was based on two sources of 1-W and 18-mW nominal power, stabilized by crystals. Good stability, low harmonic, spurious, and FM noise levels, were required from both signal and LO sources. The high power source used as LO consists of a VHF transistor crystal oscillator followed by a times 9 active multiplier. An L-band 12-W power transistor amplifier was used as a driver to a highly efficient varactor L-to-X-band multiplier. The low level signal source is similar to the power (LO) source but without the L-band transistor amplifier. Sliding short and twin stub tuners were used for impedance matching purposes so as to obtain maximum power absorption by the glow discharge lamp. Such impedance matching was carried out for each change in discharge current. The hybrid tee, tuned to the X-band test frequency, separated the LO from the signal but at the expense of 3-dB loss in the signal.

As commercial indicator lamps are much smaller than waveguide cross sections at X-band, a rather large lamp shown in Fig. 2 (NE-7 glow lamp manufactured by Signalite Inc.) was selected so as to intercept a maximal amount of the RF power. The lamp was placed in a 2-port single-ended mixer mount shown in Fig. 3 and ignited by means of a simple circuit shown in Fig. 4. The ordinary connector in the mount used for placement of diode detectors or mixers was enlarged so as to accommodate the NE-7 lamp. The electrode lengths were perpendicular to the RF Poynting vector.

As the lamp, despite its relatively large size, occupies only a small part of the waveguide cross section and thus intercepts only a corresponding portion of the transmitted RF power, sensitivity levels here are considerably less than those reported previously when waveguide mounts were not used [30]. In addition, lamp orientation in the previous experiment was such that the electrode lengths were parallel to the RF Poynting vector, thus allowing interaction of the EM radiation with the plasma over a considerably longer distance. Such an orientation here would have involved much more substantial restructuring of the waveguide mount. Hence, for the sake of convenience, the usual opening in the walls for placement of a diode was enlarged to accommodate larger glow lamps, as shown above in Fig. 3.

Response of the NE-7 glow lamp to varying signal levels P_S with a constant LO level of 20 mW is shown in Fig. 5. The RF powers are distributed over the entire waveguide cross section. The receiver, centered at the intermediate frequency, had a bandwidth of 20 kHz. The electronic noise from the lamp over a 65–85-kHz bandwidth was 23 μV. However, when the RF sources were activated, the detected noise rose slightly to 26 μV. This accounts for the decreasing slope on the left side of Fig. 5, as the measurement includes both signal and noise. The slope of the rest of Fig. 5 will be discussed later. In view

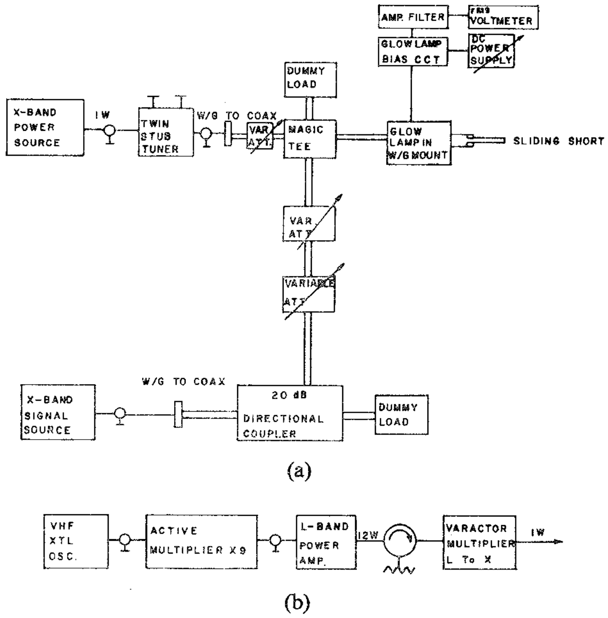


Fig. 1. Experimental setup for observing mixing efficiency of commercial glow lamps at relatively high LO power levels. (a) Microwave system test equipment. (b) X-band power source.

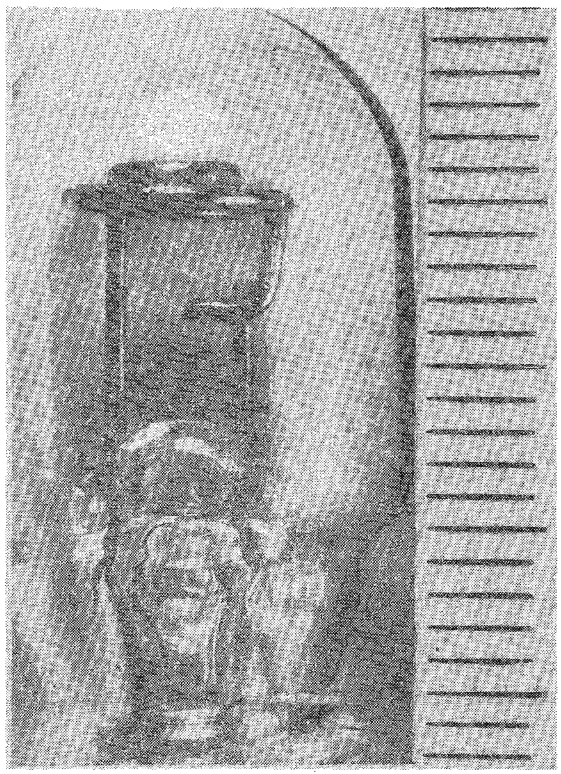
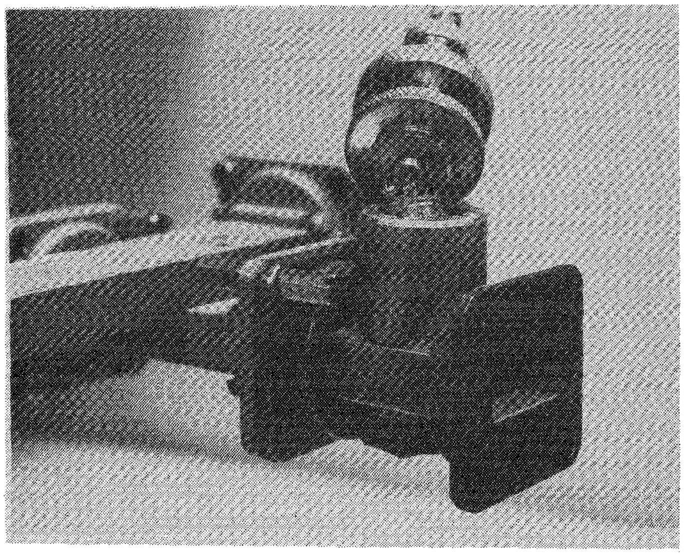
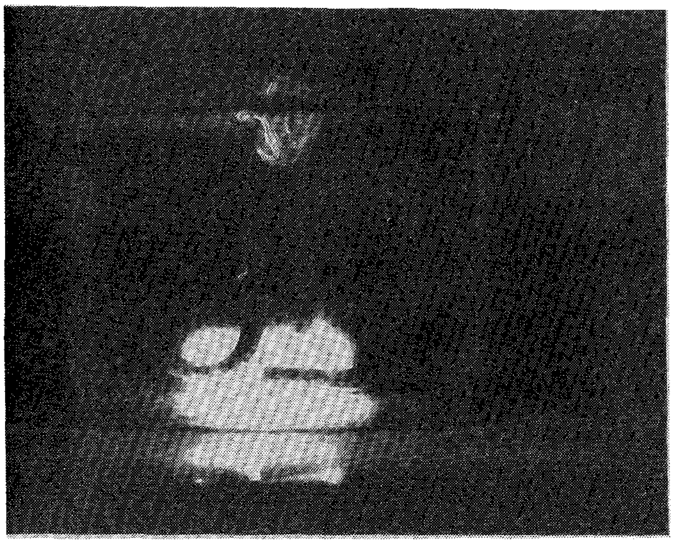


Fig. 2. Signalite Inc. NE-7 glow lamp with millimeter rule.



(a)



(b)

Fig. 3. Signalite Inc. NE-7 glow lamp and 2-port single-ended mixer mount: (a) lamp and mount; (b) lamp in mount in orientation of maximum response with $I_d = 3$ mA.

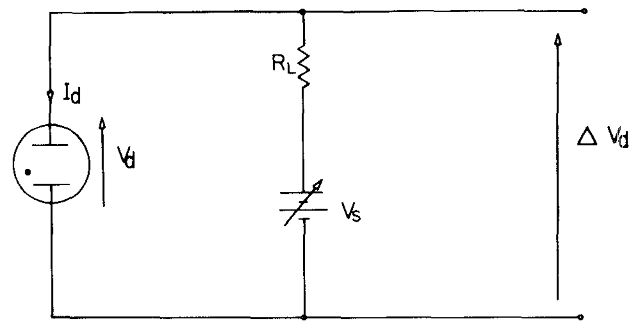


Fig. 4. Glow lamp bias circuit.

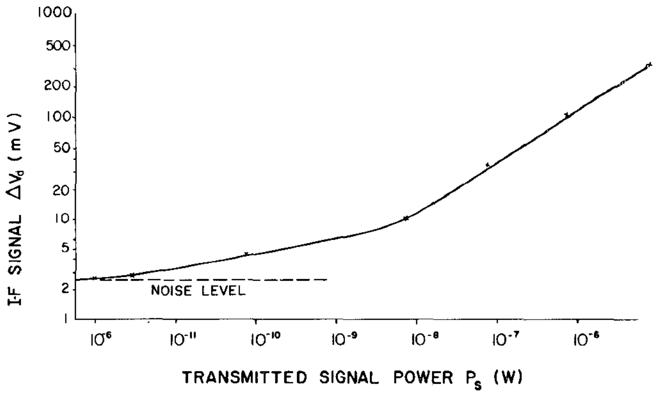


Fig. 5. IF response of NE-7 glow lamp to varying total signal power P_S transmitted through waveguide when total LO power in waveguide is constant at 20 mW. Discharge current is 3.5 mA and load resistor in circuit of Fig. 3 is 3.3 kΩ.

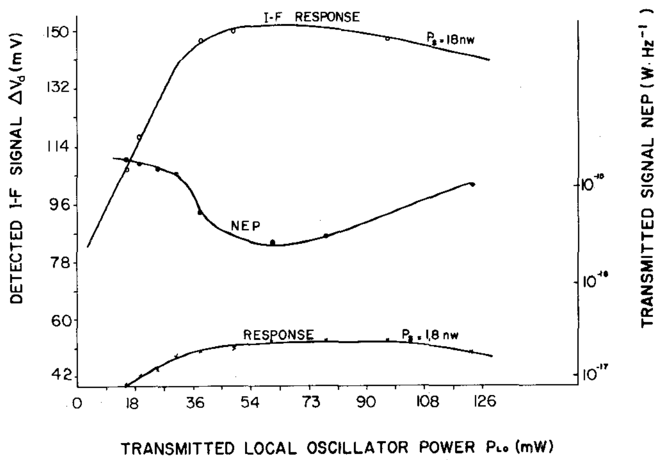


Fig. 6. Dependence of IF response and NEP on total LO radiation levels in waveguide, for NE-7 glow lamp, indicating relative conversion efficiency as a function of RF power level.

of the 20-kHz electronic bandwidth of Fig. 5, noise equivalent power (NEP) is 5×10^{-17} W·Hz^{-1}. The responsivity $|\Delta V/(P_S \cdot P_{LO})^{-1}|$ is only about 700 mV·mW^{-1}, about twenty percent of that reported previously [5] for similar electrode orientation. The reasons for such discrepancy are attributed primarily to the geometry described above.

Increasing the local oscillator 4 dB improved (decreased) the NEP the same amount, thus supporting the concept of using high LO levels to detect weak signal levels. However, when the LO level was increased by a factor of ten, the NEP observed was worse! Although in principle such power levels should not damage the lamp, nevertheless the lamp was replaced with another NE-7 glow lamp, and the high LO power still not only did not improve the NEP, it actually increased the NEP. To investigate this further, the IF response and NEP of the new lamp were observed at the same current for varying LO levels with constant signal power P_S equal to 18 nW. Fig. 6 indicates an optimum local oscillator power of about 30 mW. Although the lamp is not damaged by higher radiation levels, the mixing and thus IF conversion efficiency of the lamp are clearly reduced if the LO level is increased too high. The IF responsivity of this lamp at low LO levels is about the same as that of the previous lamp. A similar maximum of responsivity with LO power is observed when P_S is decreased by a factor of 10. The

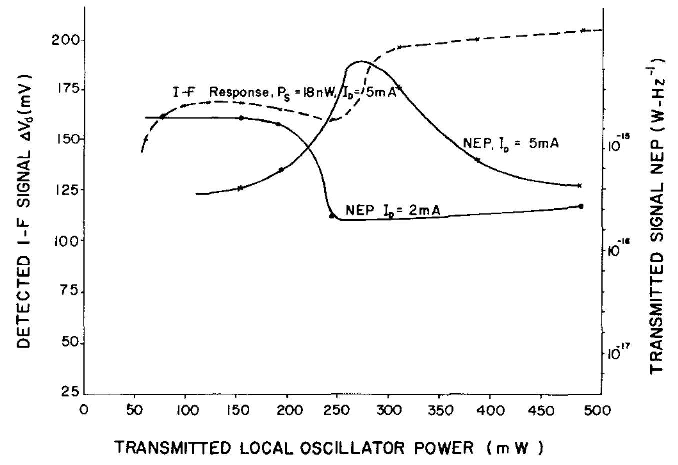


Fig. 7. Dependence of IF response and NEP on total LO levels in waveguide, with NE-7 discharge lamp current as a parameter.

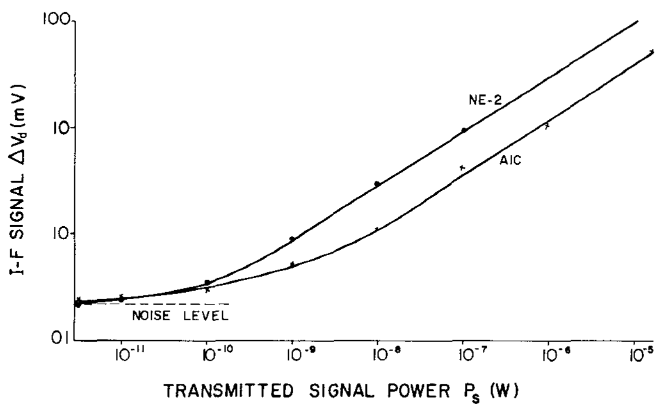


Fig. 8. Response of Signalite AIC and Alco NE-2 glow lamps to signal power in heterodyne receiver; $P_{LO}=1.45$ mW, $\omega=8.34$ GHz, $\omega_{i\text{-}f}=22$ kHz. Signal and LO powers are total values in waveguide.

dependence of NEP on LO power in Fig. 6 is as expected from the responsivity dependence on local oscillator power, and indicates response linearity still holds at higher radiation levels despite the reduced conversion efficiency; i.e., the conversion efficiency is determined by the high local oscillator level and not by P_S.

The effect of varying discharge current on conversion loss and NEP is shown in Fig. 7. It appears that a saturation level is reached at higher LO levels, and thus the potential advantage of high LO power levels to detect weak signal levels is very limited. However, increasing the discharge current does appear to have the effect of increasing the LO power level at which saturation effects begin to take place. Of course, one cannot conclude that the sensitivity is improved until the variation of noise with current is considered.

In a separate experiment the very *small* parallel-wire electrode Signalite AIC glow lamp (electrode length = 4 mm, electrode width = electrode separation = 1 mm) [31] and Alco NE-2 glow lamp were tested for IF response, as shown in Fig. 8 for the same waveguide mount. Here, the microwave frequency was 8.34 GHz, with a 22-kHz difference frequency. The electronic bandwidth was 90 kHz, thus yielding an NEP of 3.5×10^{-17} W$\cdot$Hz^{-1}. The limiting noise level of 250 μV was about 3.2 times that of the lamp alone over the same electronic bandwidth and indicates the NEP, if limited by discharge noise alone, should be 1–2 orders of magnitude less. Thus these *small* lamps, despite their miniature detecting area, yielded better sensitivity than the large NE-7 lamp with high LO levels because of a lower internal noise level.

III. Discussion of X-Band Mixing Results

Figs. 5 and 8 both indicate that, except for low P_S levels where signal approaches noise level, the response is proportional to $P_S^{1/2}$. This is to be expected for a square law device since for this case the IF voltage signal is proportional to $(P_S P_{LO})^{1/2}$. As the noise level is reached the response slopes in these figures approach zero since the rms voltmeter reading was the sum of signal and noise. However, in Fig. 5 an intermediate region of slope 1/4 on the log–log scale is indicated for P_S levels between 10^{-8} and 10^{-11} W. Such a result has been predicted in advance by a recently proposed model of detection mechanism (see [17, (48)]) based on gas breakdown enhancement by the RF field. The same model predicts an upper limit to response linearity when either of the following two conditions are violated:

$$\Delta v \ll \bar{v} \tag{1}$$

$$\Delta\epsilon \ll \bar{\epsilon}. \tag{2}$$

Here, $\bar{v}$ and $\bar{\epsilon}$ are the average random electron velocity and kinetic energy provided by the dc field, and Δv and $\Delta\epsilon$ are electron velocity and energy enhancements provided by the additional RF electric field.

When either (1) or (2) does not hold, lamp response to the RF signal becomes nonlinear. To increase the LO level at which conversion efficiency reduction sets in demands increasing the average electron energy. Increasing the discharge current affects not only electron energy but also electron number density. The electron energy is dependent also upon gas type and pressure. To design lamps for improved IF conversion efficiency at higher radiation levels requires further study. However, for a given current both Δv and $\Delta\epsilon$ *decrease* with increasing electromagnetic and collision frequencies [17]. Thus for the same discharge current in a given lamp the local oscillator power level at which conversion losses set in should increase with increasing EM frequency.

This implies improved potential sensitivity at millimeter wavelengths for increased LO power levels.

In view of the impedance matching via the stub tuner and sliding short, the relatively low sensitivity reported here for waveguide mounted lamps subject to low-intensity RF levels would indeed appear to be attributable to geometry. This can be shown by considering the incident power *density* rather than total RF power in the waveguide, not all of which is intercepted by the lamps. In this case, the power density responsivity for the linear portions of Fig. 5 for the NE-7 glow lamp is on the order of 1600

$V \cdot cm^2 \cdot W^{-1}$. For the AIC lamp of Fig. 8, which is similar to the AIB lamp, the power density responsivity is on the order of 570 $V \cdot cm^2 \cdot W^{-1}$. These figures are roughly about one order of magnitude less than the power density responsivities of the free space configuration investigated previously [30]. The latter, equal to the product of the responsivities and effective receiving areas reported there, are on the order of 6000 $V \cdot cm^2 \cdot W^{-1}$. The order of magnitude improvement for the free field case [30] should be expected on the basis of glow lamp orientation there, as described above.

Conversion gain, defined as the ratio of IF to received RF power, is equal, per watt of incident power, to $(\Delta V_d)^2/R_{eq}$, where R_{eq} is the equivalent load resistance determined by the combination of actual load resistance in parallel with glow lamp dynamic resistance. Generally, $R_{eq} \approx 100$–$500\ \Omega$ [17]. For the free-space case, where *only received* RF power was considered, conversion gain was equal to about 80 dB. The fact that this gain is greater than unity is a result of the internal signal amplification produced by the dc bias in a cascade-type collision process [17]. In this way, some dc power is converted to IF power. However, in the present case, as the lamps intercept only a small portion of the total RF power flowing through the waveguide, the conversion efficiency or gain is about 676 or 28 dB for the AIC lamp and 4900 or 37 dB for the NE-2 and NE-7 lamps for low RF power levels. For the NE-7 lamp used in Fig. 6, the responsivity for 90-mW LO power is about half that at 30-mW LO power. This implies a 6-dB decrease in conversion gain at 90 mW as compared to 30-mW LO power.

Because of the high plasma noise levels, noise figures (equal to NEP $\div kT_0$, where k is Planck's constant and T_0 is 290 K) are rather high here, being on the order of 40 dB. For the NE-2 lamp of Fig. 8, if source noise is disregarded, the noise figure is about 30 dB. About 10-dB improvement can be brought about by orientating the electrode lengths parallel to the RF Poynting vector as mentioned previously. In the present case, NEP was calculated based on *total* RF power in the waveguide. A smaller waveguide cross section, as at higher frequencies, would allow a much greater amount of RF power to be intercepted by the lamp. This would increase the conversion gain and responsivity, and thus significantly improve the NEP and noise figure. In general, these experimental results suggest that the use of commercial indicator lamps as mixers should be more promising for millimeter wave than for lower microwave frequencies. The reasons, aside from the economic standpoint, are as follows.

1) The smaller waveguide size allows such lamps to intercept almost all the RF power flowing through the waveguide.

2) Operation at high electromagnetic frequencies requires higher discharge currents [1] in order to maintain the condition $\nu \simeq \omega$, which is necessary for maximum responsivity [17], [32]–[34]. As a result, high LO levels can probably but not necessarily be maintained before conversion loss sets in.

3) With smaller waveguide cross section smaller lamps can be used, which generally imply faster speed of response [23].

4) At smaller wavelengths the EM radiation can be guided to the most sensitive region of the lamp with simple, inexpensive techniques as shown previously [2], [35] without involving waveguide cutoff problems. In this way, the RF energy can be focused along the electrode length with a much larger path through the plasma instead of propagating along the much smaller path perpendicular to the electrode length.

5) Antenna properties resulting from electrode geometry can be much more noticeable at smaller wavelengths. Optimization of such geometry should improve sensitivity significantly further [31]. In particular, it should be possible to design electrode geometry configurations to maximize conversion gain at a given millimeter wave frequency through repeated reflection of the RF signal from electrode-to-electrode, i.e., creation of a standing wave between the electrodes. For existing glow lamps, this would require a wavelength on the order of about 2 mm (150 GHz).

In this way, by focusing the RF radiation into the lamp, the high responsivity and conversion gain of these inexpensive and rugged devices can be exploited to compensate for the high noise level.

6) In addition, use of magnetic fields to obtain cyclotron resonance can improve sensitivity considerably, as shown recently [36]. This is particularly relevant for detection of high millimeter-wave frequencies with commercial lamps, where the electron collision frequency is much less than the electromagnetic frequency [36].

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