Harmonic mixing effects in Schottky diode harmonic mixers at THz frequencies

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Abstract **– We report on the breakdown of IF power for certain bias voltages for single-diode Schottky mixers at THz frequencies. This dramatic loss of IF power is due to an increase of conversion loss and is governed by intrinsic and external parameters. Based on an analytical approach utilising small signal analysis, it is possible to explain the depth of the breakdown and to estimate the voltage where the breakdown occurs. Measurements for 2nd harmonic mixers show good agreement with analytical predictions.**

I. Introduction

An interesting effect associated with submicron GaAs Schottky diodes has been found by several authors [1,2,3,4,5]. Deep breakdowns of intermediate frequency (IF) power have been observed when varying the DC bias voltage for Schottky diode harmonic mixers. Although this effect has been reported for some time, only recently has a theoretical explanation been given [4,5,6].

In the case of a fundamental mixer it is well understood that successively increasing the DC bias voltage or the DC bias current, respectively, yields an IF power output with a broad maximum (Fig. 1, upper curve). In contrast to that behaviour, it has been observed that under certain bias conditions the same diodes reveal a significant breakdown of IF power when operated as harmonic mixers at THz frequencies. In the case of a single-diode 2nd harmonic mixer, one IF power minimum with different depths can be observed, depending on the diode used (Fig. 2). This breakdown of IF power can be explained by small-signal analysis taking into account different mixing paths to convert power from signal frequencies into intermediate frequencies.

II. Experimental set-up

The diodes were measured in a set-up with two far-infrared (FIR) gas lasers as CW radiation sources. The FIR lasers were pumped with two CW CO_2 lasers. The laser assigned as a local oscillator (LO) was emitting at 693 GHz, whereas the 'RF' laser was operating at 1397 GHz. For comparison, the diodes were also measured as fundamental mixers with both lasers emitting at 2523 GHz and the two lasers slightly detuned yielding an IF of 1 MHz. Additionally, Schottky diodes have been measured operated as 4th harmonic mixers. Again, one laser was emitting at 693 GHz whereas the second frequency of 171.8 GHz was generated by a klystron.

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Table 1: Diode parameters

Diode name		1I7	1I12	J118	1T12	1T14	1T15	1T23
Producer		UVA	UVA	MIT	UVA	UVA	UVA	UVA
Anode diameter	d_A in μm	0.8	0.45	1.0	0.5	0.5	0.25	0.25
Doping epitaxial layer	N_d in 10^{17} cm^{-3}	3	4.5	1	3	10	10	10
Thickness epitaxial layer	w_{epi} in A	1000	600	1000	750	450	300	300
Zero-bias capacitance	C_{j0} in fF	0.9-1.2	0.45	1.8	0.5	0.85	0.25	0.5
Series resistance	R_s in Ω	13	33	30	28	10	20	30
Ideality coefficient	η	1.3	1.4	1.15	1.22	1.5	1.5	1.6

The whisker-contacted diodes were mounted on a corner-cube reflector to couple the radiation into the submicron diameter-sized diodes. All measurements were performed at ambient temperatures. Diode parameters together with data provided by the manufacturers can be taken from Table 1. The experimental set-up is described in greater detail in [4]. Details about the Schottky diodes and their manufacturing process can be found in [7,8].

III. Small-Signal Analysis

Following the notation of [9], a 2nd harmonic mixer can be described using the admittance matrix $\mathbf{Y}$, which connects the small-signal voltages V_m and currents I_j at the different side-band frequencies

$$\omega_m = \left| m\,\omega_{LO} + \omega_{IF} \right| \tag{1}$$

with ω_{IF} the intermediate frequency. For a 2nd harmonic mixer with a RF frequency at the second upper side-band

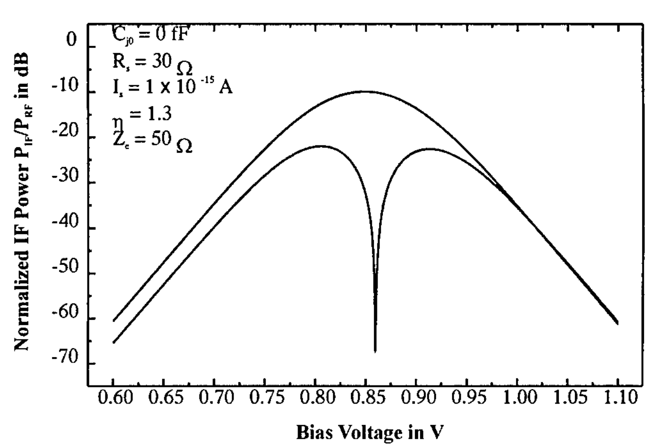

Fig. 1: Calculation of normalised IF power vs. bias voltage for a fundamental (upper curve) and a 2nd harmonic (lower curve) mixer.

of the LO frequency with all the lower side-bands $(m<0)$ as well as side-bands higher than the second upper side-band $(m>2)$ shorted out, the augmented matrix, $\mathbf{Y}'$, can be written as

$$\begin{bmatrix} I_2' \\ I_1' \\ I_0' \end{bmatrix} = \begin{bmatrix} Y_{22}' & Y_{21}' & Y_{20}' \\ Y_{12}' & Y_{11}' & Y_{10}' \\ Y_{02}' & Y_{01}' & Y_{00}' \end{bmatrix} \begin{bmatrix} V_2' \\ V_1' \\ V_0' \end{bmatrix} \tag{2}$$

For $\mathbf{Y}'$, the embedding impedances and the series resistances of each port are included in the network [9]. Unlike a fundamental mixer, there are no *external* currents at the LO side-bands, hence I_1' equals zero. By eliminating V_1', equation (2) can thus be reduced to a 2 x 2 matrix:

$$\begin{bmatrix} I_2'' \\ I_0'' \end{bmatrix} = \begin{bmatrix} Y_{22}'' & Y_{20}'' \\ Y_{02}'' & Y_{00}'' \end{bmatrix} \begin{bmatrix} V_2'' \\ V_0'' \end{bmatrix} \tag{3}$$

with the elements of the reduced matrix, $\mathbf{Y}''$, of the form

$$Y_{20}'' = Y_{20}' - \frac{Y_{21}'\, Y_{10}'}{Y_{11}'} \tag{4}$$

Here, Y_{20}' represents the 'standard' mixing path for power converted from the RF frequency by mixing with the doubled LO frequency to the IF frequency. The second expression in equation (4) represents another mixing path from the RF frequency to the LO upper side-band frequency, ω_1, and from there down to the IF frequency. If the two existing paths possess the same overall admittance the conversion efficiency will be zero.

According to [9], for the case of a 2nd harmonic mixer the mixer conversion loss, L_{02}, is:

$$L_{02} = \frac{|Z_{RF} + R_{s2}|^2\, |Z_{IF} + R_{s0}|^2}{4\, |Z_{02}''|\, \mathrm{Re}(Z_{RF})\, \mathrm{Re}(Z_{IF})} \tag{5}$$

with Z_{RF} and Z_{IF} the embedding impedances at the RF and the IF frequencies and R_{s2} and R_{s0} the respective series resistances. Z_{02}'' represents the impedance matrix element connecting the exciting RF current with the IF small-signal voltage. It can be calculated by inverting equation (3) taking into account the impedance matrix, $\mathbf{Z}$, being the inverse of the admittance matrix, $\mathbf{Y}$. Z_{02}'' can be calculated using

$$Y_{mn}' = G_{m-n} + i\,(\omega_{IF} + m\,\omega_{LO})\, C_{m-n} + \delta_{mn} \frac{1}{R_{sm} + Z_{em}} \tag{6}$$

with G_m, and C_m being the fourier coefficients of the time-dependent conductance G_j and capacitance C_j.

For known diode's *I-V* and *C-V* characteristics one can then calculate the IF power of a mixer without any numerical means. This has been done for some typical diode parameters with the zero-bias capacitance neglected (Fig. 1). As can be seen from the lower curve, a deep breakdown of the IF power appears for a harmonic mixer. This phenomenon has also been found experimentally (Fig. 2).

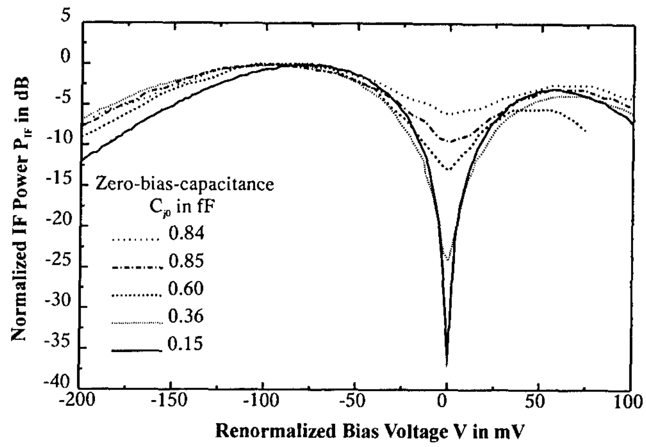

Fig. 2: Measured IF power vs. bias voltage for diodes with different zero-bias capacitances. The curves are normalised to their maximum power and overlaid at their breakdown voltage.

Now, looking at Fig. 3 gives evidence of the above stated suggestion that the two competing mixing paths lead to the breakdown of IF power. There exists a bias voltage where the two admittances have the same magnitude and are real due to the negligence of the capacitive mixing branch. This leads to an overall admittance null and thus to a null of the diode's impedance matrix element at exactly that bias voltage. On the other hand, by inserting very small diode impedances into equation (5) it is obvious that this leads to high conversion losses.

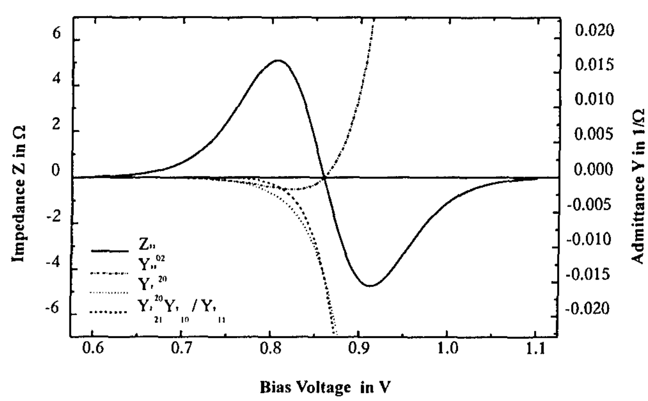

Fig. 3: Diode impedance and admittances as a function of bias voltage for a 2nd harmonic mixer.

IV. Real Diodes

When comparing diodes with different zero-voltage capacitances, another interesting effect arises. As can be seen from Fig. 2, the depth of the measured IF power breakdown strongly depends on the zero-bias capacitance. It can be seen, in principle, that a smaller zero-bias capacitance results in a deeper minimum of the IF power. For the diode with the smallest zero-bias capacitance (0.15 fF), an overall depth of the IF power breakdown of as much as 36 dB could be measured. This phenomenon can be explained by having a closer look at the capacitive mixing branch.

Usually, the classical one-over-square-root-type *C-V* characteristic is assumed [9]. This yields reasonable results for small bias voltages far off the flat-band condition. For forward bias voltages near the flat-band condition, this approach yields unreasonably high barrier capacitances. In order to avoid this singularity, an exponential diode *C-V* characteristic has been used that has been fitted to the so-called refined capacitance [4,5]. This refined capacitance takes into account real charge distributions through the depletion layer [10] and leads to finite barrier capacitances under flat-band conditions. Now, this approximated barrier capacitance without singularities can be used in the analytical determination of the conversion matrices.

Looking at the impedance matrix element, it can be seen that, by introducing a capacitive admittance, the impedance matrix element becomes complex. The absolute value of the impedance matrix element is not zero anymore at the IF power breakdown voltage and, therefore, the breakdown itself is not as deep as without capacitive elements.

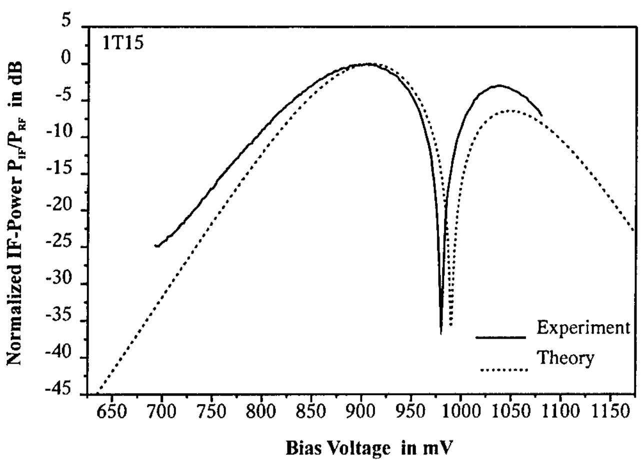

Fig. 4: Measured and calculated normalised IF power vs. bias voltage for the diode 1T15.

The reason for that behaviour can be found by looking at equation (6). It can be shown analytically that both fourier components of the conductance G_m and the capacitance C_m are either real or imaginary for the same side-band index *m*. Because they are connected via the complex number *i*, the overall admittance matrix element and, thus, the impedance matrix element is complex whenever G_m and C_m are present at the same time. The absolute value of the complex impedance matrix element, on the other hand, yields zero only if the real part as well the imaginary part become zero for the same bias voltage. When a capacitive conductance is inserted, this still results in a minimum of the impedance matrix element but the IF power does not fall off to such an extent anymore. This now explains the experimental results of the dependency of the depth of the IF power breakdown on the zero-voltage capacitance in Fig. 2.

The results for a diode with a small zero-bias capacitance (1T15) can be seen in Fig. 4. Similar curves have been gained for all diodes. Keeping in mind the simplifications made, good matching of measured and calculated curve can be observed.

In general, all expressions in equation (6) which add an imaginary contribution to the diode's conductance have an effect on the admittance matrix element and therefore on the breakdown depth. I.e. have there been measured deeper breakdown depths for lower LO frequencies while keeping all the other parameters constant [4].

V. Voltage Position

After considering the depth of the IF power breakdown, an expression shall be given to estimate the bias voltage where the IF power breakdown occurs. Looking at equation (5) shows that large conversion losses and, hence, low IF power occur when Z''_{02} is small. Thus, Z''_{02} can be calculated using equations (3) and (6). From that it can be seen that Z''_{02} is small when also Y''_{20} is small. Therefore, Y''_{20} has been set to zero in order to solve this equation for the bias voltage. Again, the diode capacitance has been neglected because it only has a small effect on the IF power breakdown voltage, V_{Min}:

$$V_{Min} = \frac{\eta kT}{e} \times \ln\left\{ \frac{\left(\frac{\eta kT}{eI_s} \mathrm{I}_2\left(\frac{eV_{LO}}{\eta kT}\right)\right)}{\left(\begin{array}{l}(R_{s1}+Z_{e1})\,\mathrm{I}_1^2\left(\frac{eV_{LO}}{\eta kT}\right) \\ -(R_{s1}+Z_{e1})\,\mathrm{I}_0\left(\frac{eV_{LO}}{\eta kT}\right)\frac{\eta kT}{eI_s}\mathrm{I}_2\left(\frac{eV_{LO}}{\eta kT}\right)\end{array}\right)} \right\} \qquad (7)$$

I_n is the modified Bessel function of the first kind of the *n*-th order and V_{LO} is the intrinsic voltage across the diode's depletion layer induced by the LO's electromagnetic field. As can be seen does V_{Min} depend on diode parameters such as ideality coefficient, saturation current, I_s, series resistance, embedding impedance as well as externally determined parameters such as the diode voltage V_{LO}. *T*, e and *k* are the temperature, the electronic charge and Boltzmann's constant, respectively.

In Fig. 5, the bias voltage at IF power breakdown, V_{Min}, has been plotted as a function of the local oscillator voltage for four different diodes. V_{LO} has been calculated from the measured bias voltage drop induced by the local oscillator when having a constant bias current source. An

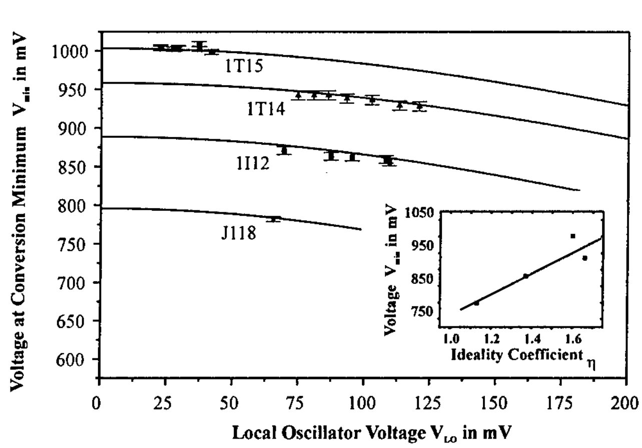

Fig. 5: Measured and calculated IF power breakdown voltages vs. local oscillator voltage.

excellent match of the predicted and the measured IF power breakdown voltages can be found, though several simplifications have been made in the theoretical model.

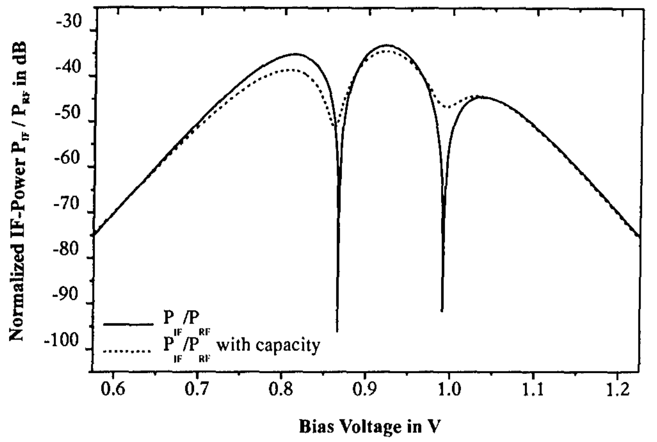

Fig. 6: Calculated IF power vs. bias voltage for a 3rd harmonic mixer.

VI. HIGHER HARMONICS

Calculating a 3rd harmonic mixer one can apply the same procedure as for a 2nd harmonic mixer. Calculations of the corresponding curves for some typical diode parameters with and without diode capacitance reveal the existence of now two IF power minima (Fig. 6). The existence of two minima for a 3rd harmonic mixer and one minimum for a 2nd harmonic mixer confirms the phenomenological law introduced in [6] that a N-th harmonic mixer produces N-1 IF power breakdowns. This behaviour has also been confirmed through numerical harmonic balance analysis.

Unfortunately, no appropriate FIR laser lines were available to measure these effects for a 3rd harmonic mixer. A 4th harmonic mixing experiment has been carried out instead. It can be seen in Fig. 7 that three IF power minima arise for this 4th harmonic mixer. This is a

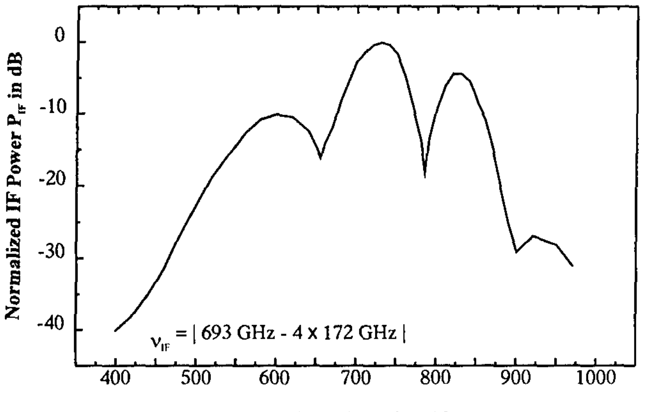

Fig. 7: Measured normalised IF power vs. bias voltage for a 4th harmonic mixer.

further strong evidence for the above-mentioned phenomenological N-1 law.

VII. CONCLUSION

The mixing behaviour of single-diode harmonic Schottky mixers has been investigated analytically and experimentally. It has been shown that N-th harmonic mixers produce N-1 IF power minima when the diode's bias voltage is varied. This has been confirmed by an analytical description for a 2nd and a 3rd harmonic mixer and through experimental results for a 2nd and a 4th harmonic mixer. The reason for these minima is a cancellation of power due to the competition of different mixing paths leading to an increased conversion loss. The depth of the IF power breakdown depends on the diode's barrier capacitance and other parameters adding to the imaginary part of the admittance. Furthermore, an approximation formula has been given with which it is possible to predict the bias voltage for the IF power minimum for a 2nd harmonic mixer. Comparison of measured and calculated curves shows good agreement.

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