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Three-terminal junctions operating as mixers, frequency doublers and detectors: a broad-band frequency numerical and experimental study at room temperature

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Abstract

The frequency response of nanometric T- and Y-shaped three-terminal junctions (TTJs) is investigated experimentally and numerically. In virtue of the parabolic down-bending of the output voltage of the central branch obtained at room temperature under a push–pull fashion input, we analyse the low-frequency performance (<1 MHz) of TTJs operating as mixers, their RF capability as doublers up to 4 GHz and detection at 94 GHz. Special attention is paid to the impedance matching and cut-off frequency of the measurement setup. The numerical study is carried out by means of Monte Carlo simulations. We illustrate the intrinsic functionality of the device as frequency doubler or rectifier up to THz. The role of the width of the central branch on the high-frequency response is also explored, finding different cut-off frequencies for doubling and detection as a consequence of the diverse working principles of both mechanisms and the particular geometry of the TTJs.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In modern electronics the miniaturization for present lithographic processes is reaching the nanometre size. At this scale, devices are based on novel working principles, in which surface and quantum effects play a key role on their final behaviour. Within this frame, nanodevices based on semiconductor heterostructures called three-terminal junction (TTJ) [1, 2] are emerging as potential building blocks of analogue and digital integrated circuits. The III-V heterostructure creates a high-mobility 2DEG layer in which electrons can move overcoming very few scattering

events. This ballistic or quasiballistic transport of electrons inside the devices and their particular geometry (T- or Y-shaped) provoke an attractive and robust nonlinear response of TTJs confirmed by theory [3], numerical simulations [4] and experiments [5]. Therefore, the use of high-electron-mobility InGaAs channels with high indium content (providing mobilities in excess of $10\,000\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$ at 300 K, with the advantage of being compatible with advanced HEMT technology) is key for improved operation of these devices at room temperature. Another advantage of TTJs in comparison with conventional devices arises from its small size, which allows a high integration density and a high intrinsic operation speed.

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Several possible applications of TTJs have been demonstrated by different authors: rectification up to 94 GHz at room temperature [6], frequency doubling in the range of 20 MHz–1 GHz [7] and logic circuits as a NAND gate [8], a half-adder [9] or a set–reset (SR) latch [10]. Similarly GaAs-based three-terminal nanowire junctions controlled by Schottky wrap gates (WPGs) [11] are known to operate as Boolean gates [12]. Also recently, power gain at room temperature up to 1.5 GHz has been measured in TTJs [13], remarkably demonstrating their capability to act as active devices. Frequency mixing at low frequency [14] has also been measured, but with significant signal decay, attributed to a mismatching problem. Finally, Monte Carlo (MC) simulations have shown that ballistic nanodevices can have intrinsic cut-off frequencies above 1 THz [15]. Understanding the limits of the dynamic performance of TTJs will be the objective of this paper since not much effort has been put till now to study the response of TTJs at very high frequency, approaching the THz range.

This paper describes our study, both experimental and numerical, of the frequency performance of TTJs operating as mixers, doublers and detectors in several frequency bands, ranging from a fraction of a kHz to 94 GHz, and with different experimental setups. All measurements and simulations are performed at room temperature. The paper is organized as follows. In section 2 we provide a brief description of the fabrication process, simulation method and working principle of TTJs. Section 3 describes how the device operates as a mixer at low frequency (<1 MHz). This low-frequency experiment will be used to illustrate the influence of the equipment on the effective cut-off frequency of the mixing setup. Then, frequency doubling and phase detection will be demonstrated at an intermediate frequency of 4 GHz. To conclude with the experimental work we will show how an optimized structure with reduced parasitics can operate as a detector at much higher frequencies, experimentally reaching 94 GHz (limit of the equipment). The possibility of intrinsic operation (parasitic capacitances, accesses and cables are not included in simulations) at frequencies approaching the THz range is finally explored by means of MC simulations. Also the influence of the width of the vertical stem of the TTJ is analysed. Finally section 5 draws the most important conclusions of this work.

2. Experimental, simulation method and device operation principle

2.1. TTJ fabrication process

The InGaAs/InAlAs heterostructure on which the fabricated TTJ is based was grown by molecular beam epitaxy (MBE) at the IEMN [16]. An indium content of 75% in the InGaAs channel is used in order to obtain high electron mobility ($10\,000\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$) and sheet electron density ($2.65 \times 10^{12}\text{ cm}^{-2}$). The geometry of the TTJ is defined with a high-resolution negative resist, hydrogen silsesquioxane exposed by electron beam lithography with a Leica EBPG5000+, followed by dry etching with a $\text{CH}_4/\text{H}_2/\text{Ar}$ plasma. This

solution has been preferred to wet etching because it provides lower edge roughness and a better control of undercut. A Ni–Ge–Au–Ni–Au metal sequence is then deposited by evaporation and is annealed at 300 °C with a N_2H_2 gas to form ohmic contacts. Finally, Ti–Au bonding pads are evaporated.

2.2. Monte Carlo simulator

The MC simulations, based on a semiclassical transport description, allow us to get a detailed insight into the processes taking place inside the devices, thus allowing the determination of the optimum topologies of the TTJs for high-frequency applications. Our MC simulator is self-consistently coupled with a 2D Poisson solver [17]. The model contains all the necessary ingredients for the correct modelling of ballistic devices such as accurate models for ionized impurity, alloy, polar and nonpolar optical phonon, acoustic phonon and intervalley scattering, consideration of Γ -L-X nonparabolic spherical valleys and appropriate carrier injection techniques at the contacts. Surface charges appearing at the semiconductor interfaces with dielectrics (crucial when the size is reduced up to the nanoscale) are also self-consistently included in the simulations [18]. When analysing the response of TTJs at very high frequency (section 4), the profile of the surface charge used in the simulation is frozen to that previously calculated under equilibrium conditions, since the typical capture/emission times of the surface states are about 1 μs , several orders of magnitude longer than the maximum period used for exciting the TTJ (1 ns). This approximation is in good agreement with recent simulations of the role played by dynamically adapted surface charges at these high frequencies [19, 20].

Even if the structures under analysis would require 3D simulations to exactly reproduce their topology, a 2D simulator has been used. The limitations of this simulator have been overcome by performing ‘front-view’ and ‘top-view’ consistent simulations [21]. This work focuses on top-view simulations in which the real layer structure is not included, and only the high mobility channel with its special geometry (playing a key role) will be simulated. More details of the simulations can be found in [4, 21]. The validity of this approach has been successfully checked in previous works by means of the comparison with experimental results [18, 22, 23], predicting excellent high-frequency performances for ballistic nanodevices, in some cases reaching the THz range [15, 24]. In addition, our approach has recently been further validated by the results of Sadi *et al* [19]. Using a 3D model (including our self-consistent model (SCCM) to incorporate surface charge effects) they have almost perfectly replicated the results obtained with our 2D model for the same set of T-shaped TTJ junctions [18].

2.3. Device operation principle

Our device consists of three branches connected with T- or Y-shaped geometry. In big devices, where the mean free path (l_m) is smaller than the distance between the contacts, each branch can be represented by a resistance (figure 1(a)). So,

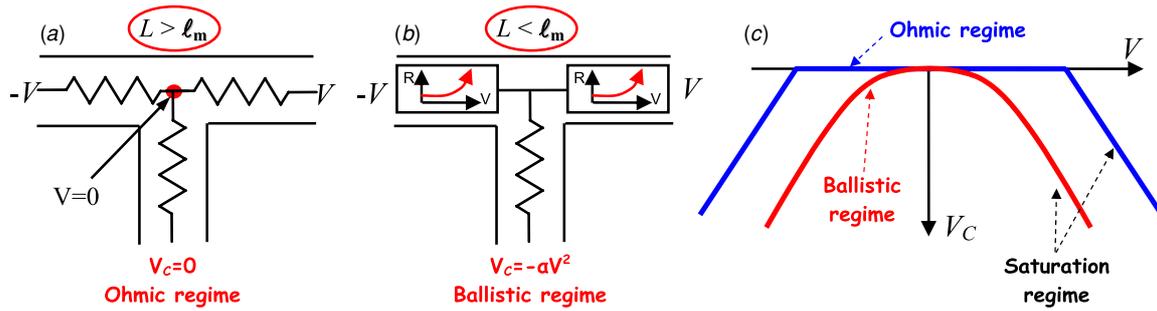


Figure 1. Sketch of the (a) ohmic and (b) ballistic regimes of transport in TtJs and the (c) V_C response for both types of transport.

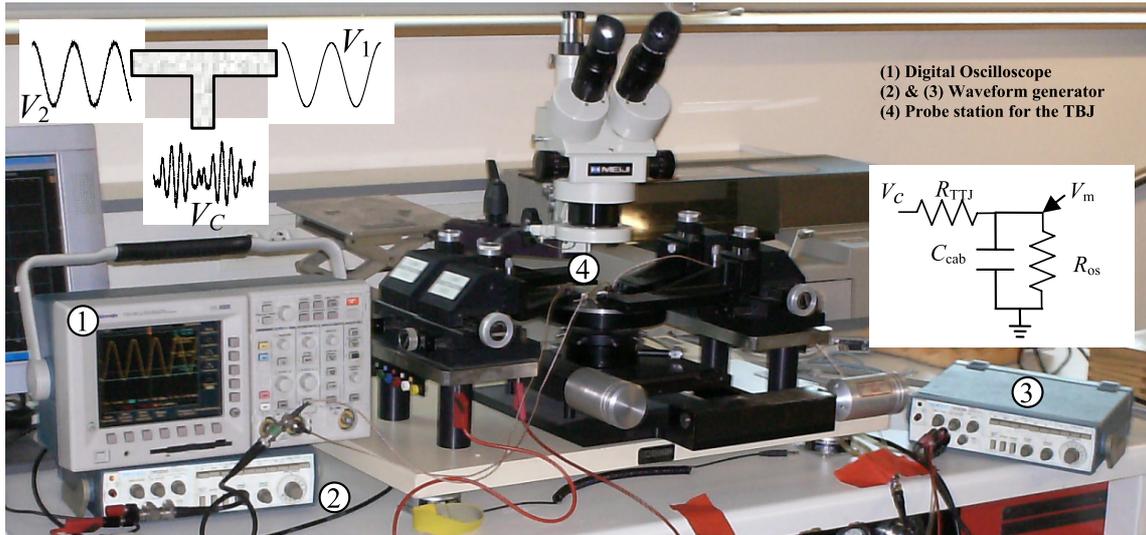


Figure 2. Experimental setup for the analysis of frequency mixing. The TtJ situated in the probe station is excited by two Tektronix CFG 250 waveform generators. The output is measured by a Tektronix TDS3012 oscilloscope. A simple circuit representation of the measurement setup is shown in the right inset.

if we apply two separate potentials with opposite sign to the right and left terminals (push–pull fashion), the potential in the middle of the junction is zero. In this ohmic transport regime, the potential measured at the bottom of the open-circuited central branch (stem), V_C , is also zero (figure 1(c)). However, when the lengths of the branches, L , are smaller than the mean free path, transport can no longer be considered diffusive, but ballistic or quasiballistic. In this regime, the horizontal branches can be considered as nonlinear resistances $R(V)$ [25], figure 1(b), and as shown by the experiments [1, 2, 5] and theory [26], V_C is always negative and varies quadratically with the input $V_C = -\alpha V^2 + O(V^4)$, figure 1(c). The origin of this phenomenon has been explained by means of MC simulations [4, 18], and it is related to the asymmetric profile of electron concentration along the horizontal branches, being higher near the negative electrode due to (i) ballistic transport and (ii) an asymmetric distribution of surface charges. This property of TtJs can be exploited to perform several analogue and digital functions such as mixing [14], frequency doubling [7, 27], high-frequency detection [6], NAND [8, 12] or NOR gates [28], etc.

It is important to remark that, as sketched in figure 1(c), when increasing the bias ($V > 0.5$ V), even in the ballistic TtJs, the response of V_C becomes linear with V due to the

appearance of intervalley scattering mechanisms that lead to the emergence of an accumulation domain near the positive electrode completely screening the variation of the potential drop between the central branch and the negative electrode [5, 22]. This mechanism is also responsible for the saturation of the current and the surprising negative values of V_C (since they are expected to be ohmic) measured in large size TtJs [5, 22]. Another important feature of the TtJ behaviour is that, contrary to the expectations, the central branch is not exactly a potential probe which measures the potential at the middle of the TtJ. Instead, surface charge effects at the stem boundaries provoke that the potential drop along the vertical branch is not equal for all the biasings, so that the value of V_C is not a direct transmission of the potential at the centre of the TtJs, and therefore depends on the stem width [18].

As a summary, we can state that the nonlinearities of these devices can be explained in terms of the broken device symmetry as a result of inhomogeneous electron concentration given by a complex mix of electron ballistic transport and surface-charge effects. Finally, the robustness of the TBJ's nonlinear response observed in experiments over a wide range of channel sizes [5, 22, 23, 29] is a unique advantage in terms of realizing room-temperature integrated circuitry using TBJs.

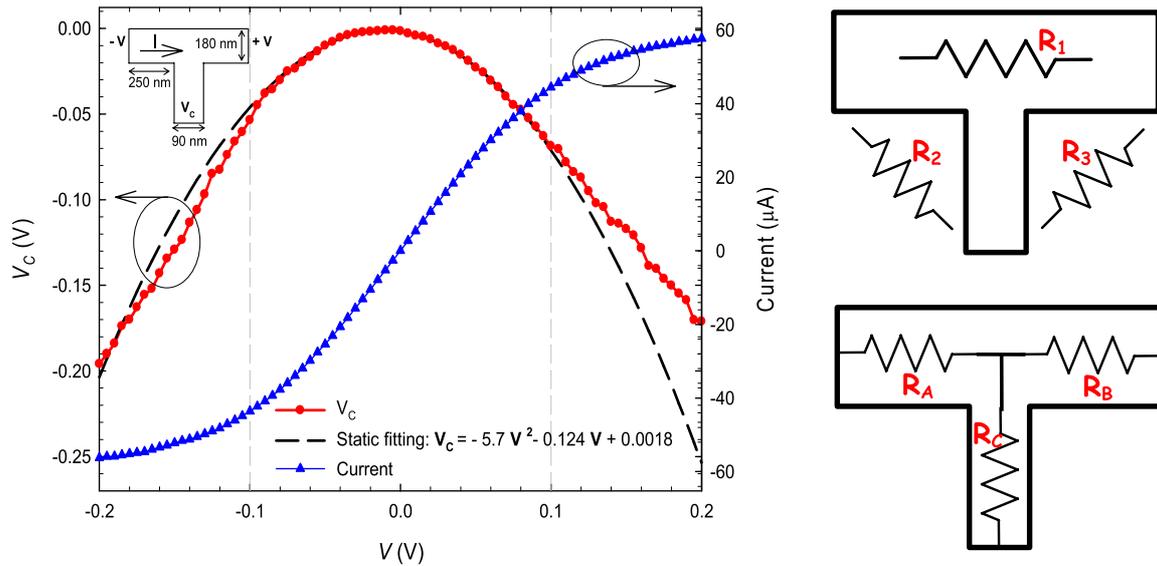


Figure 3. Static V_C - V and I - V characteristics measured in the TTJ under analysis, sketched in the top-left corner. The analytical fitting for V_C is also plotted. Right panel: representation of the resistances measured between contacts R_1 , R_2 , R_3 , and the resistances of each branch R_A , R_B , R_C . The conversion between both sets is given by $R_1 = R_A + R_B$, $R_2 = R_A + R_C$ and $R_3 = R_B + R_C$.

3. Measurements

This section describes several experiments that investigate the dynamic response of the TTJs in a broad frequency range, the ultimate goal being the integration into THz nanosystems. These nanoscale devices can reach extremely high frequencies of operation mainly because of the small electron transit time (as a result of the ballistically high electron velocity). However, due to the small width of the channels, TTJs show relatively high impedances, ranging from a few $k\Omega$ to $M\Omega$. From the point of view of circuit design this poses a serious problem of impedance mismatching when driving the load. So first we will show, for frequency mixing and relatively low frequencies (<1 MHz), how the experimental setup can distort the characterization process.

With a correct design of the coplanar waveguide accesses to the active region of the TTJ, the crosstalk capacitances, parasitic resistances and mismatching effects can be minimized. In the second subsection two experiments at much higher frequencies (4 and 94 GHz) showing those improvements are shown. However, even for a combination of low capacitive coupling between input and output electrodes (crosstalk capacitances around 1 fF) and relative low impedance (around 1 $k\Omega$) the cut-off frequency estimated from the RC time is still very low, about 160 GHz, so that other approaches should be foreseen if aiming at the THz range (for example the use of multichannel structures [11]).

3.1. Mixing

Mixers are essential components for telecommunication applications. Heterodyne mixers are present in all modern receivers. A device with nonlinear response is essential to obtain at the output a combination of the frequencies of the two input signals. The well-known parabolic response found

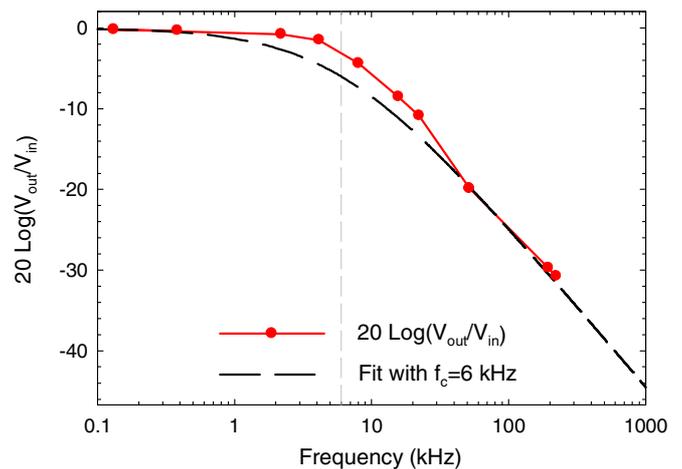


Figure 4. Voltage gain in dB of the TTJ of figure 3 as a function of the frequency f of the applied signal. V_{out} is calculated as the amplitude of the signal found at the bottom of the central branch when a voltage $V = V_{in}\cos(2\pi ft)$ is applied to one of the horizontal branches and the other is left open ($V_{in} = 100$ mV). The cut-off frequency is estimated by fitting the MC results to a $1/(1+f/f_c)$ decay.

in the output voltage of TTJs (measured at the open-circuited bottom branch) under push-pull bias (of the left and right branches) offers the possibility of fabricating frequency mixers in which both the original input frequencies and their sum and difference will be displayed at the output. In order to demonstrate this capability we apply two sinusoidal signals with the same amplitude A and different frequencies f_1 and f_2 , $V_1 = A\cos(2\pi f_1 t)$ and $V_2 = A\cos(2\pi f_2 t)$, to the left and right branches of a TTJ, respectively, as sketched in the top-left inset of figure 2. As the static response of the TTJ can be approximated by $V_C = -\alpha V^2 + bV + c$, where α is the curvature of the response, b represents the asymmetry of the junction and c is a constant accounting for the offset of

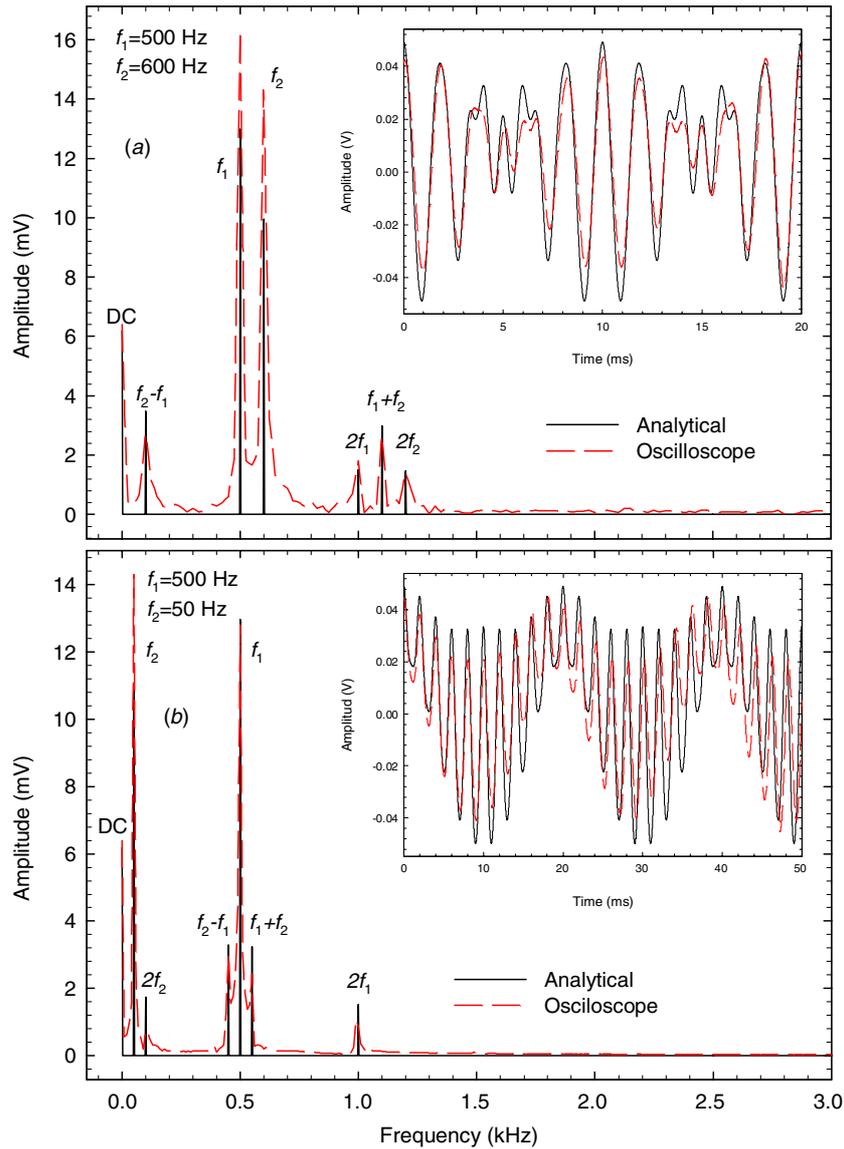


Figure 5. Frequency and time (inset) domain response of the TTI of figure 3 as measured with the oscilloscope and obtained from the analytical model, respectively, for $A = 100$ mV, $f_1 = 500$ Hz and (a) $f_2 = 600$ Hz, (b) $f_2 = 50$ kHz.

the setup, with V the push–pull input voltage, $V_1 - V_2 = 2$ V, the stem voltage V_C should show a value

$$V_C = -\alpha \left(\frac{V_1 - V_2}{2} \right)^2 + \frac{V_1 + V_2}{2} + b \frac{V_1 - V_2}{2} + c. \quad (1)$$

The term $(V_1 + V_2)/2$ must also be considered to include the effect of the offset of the input bias. From this expression it is easy to obtain that the amplitude of the output spectral components in our case should be $\alpha A^2/4 + c$ for dc, $A(1+b)/2$ for f_1 , $A(1-b)/2$ for f_2 , $\alpha A^2/4$ for $f_1 + f_2$ and $f_2 - f_1$, and $\alpha A^2/8$ for $2f_1$ and $2f_2$. We will check the presence of this frequency spectrum in measurements performed in a T-shaped nanojunction with 180 nm wide and 250 nm long horizontal branches, and a 90 nm wide vertical branch. This TTI has firstly been characterized under static conditions. The potential at the bottom of the central branch and the current in the horizontal branch measured with an HP Agilent 4142B modular dc source when biasing left and right branches in

push–pull is represented in figure 3. The fitting to $V_C = -\alpha V^2 + bV + c$ in the range of ± 100 mV (that covered by the mixing experiment) is also shown in the figure, with $\alpha = 5.7$ V⁻¹, $b = -0.124$, $c = 1.8$ mV.

Next, the experimental setup of figure 2 is used to verify the mixing response of the TTI. All measurements are performed at room temperature and in darkness. The right inset of figure 2 represents the equivalent circuit of the measurement setup. R_{os} is the input impedance of the oscilloscope, R_{TTJ} the output impedance of the junction, C_{cab} the capacitance of the cables and the rest of equipment and V_m the measured potential. The equivalent circuit simply shows that at zero frequency V_m is given by $V_C \times R_{os} / (R_{os} + R_{TTJ})$. When the frequency of the input signals increases, the $R_{os} C_{cab}$ network of the equipment causes a decay in the measured potential. In order to estimate the TTI output impedance, R_{TTJ} , the resistances between each two contacts (the third contact is open circuited) have been measured, giving the following

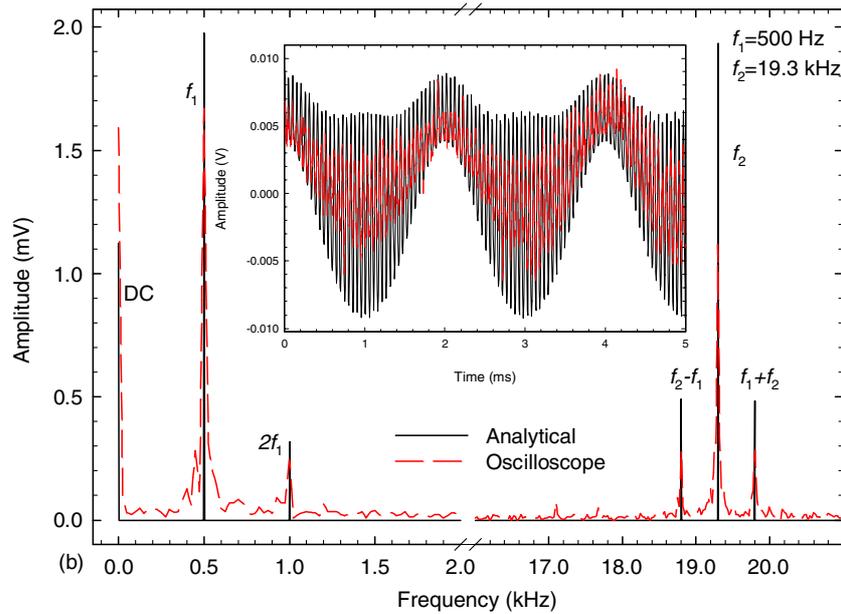


Figure 6. Frequency and time (inset) domain response of the TTJ of figure 3 as measured with the oscilloscope and obtained from the analytical model, respectively, for $A = 100$ mV, $f_1 = 500$ Hz and $f_2 = 19.3$ kHz.

values: $R_1 = 3.7$ k Ω and $R_2 = R_3 \approx 1$ M Ω . Then, by a simple mathematical conversion (following the scheme of figure 3), the resistance of each branch is obtained: $R_C = 1$ M Ω and $R_A = R_B = 1.85$ k Ω , thus providing a value for $R_{TTJ} = R_C + R_A \parallel R_B$ of around 1 M Ω . To determine the cut-off frequency, f_c , associated with the capacitance of the external cables, the amplitude at the output has been measured leaving open one of the inputs and applying a 100 mV sinusoidal signal of increasing frequency to the other. The estimated f_c is about 6 kHz, as observed in figure 4, that, using the expression $f_c = 1/(2\pi R_{os} C_{cab})$ since the device capacitances are very low (of the order of fF), provides a value for C_{cab} of 26 pF, which is completely reasonable, bearing in mind that we are employing a fraction of metre of cables of 40–80 pF m $^{-1}$. The impedance of the oscilloscope used for the measurements is $R_{os} = 1$ M Ω , so that at low frequency the measured potential V_m is about half of V_C .

Figure 5 shows the comparison of the response predicted by equation (1) using the parameters obtained from the fitting of the static V_C - V curve, with the measurements of frequency mixing for different values of the amplitude (A) and frequencies (f_1 and f_2) of the input signals. In order to obtain the spectrum of the output signal, a discrete fast Fourier transform (FFT) based on the Cooley–Tukey algorithm [30] is applied to the time domain data of the oscilloscope. In the analytical results, the influence of R_{TTJ} , the decay associated with the pole (we divide the spectra by $1+f/f_c$) and a factor 2 because of the Fourier transform (having sense only for positive frequencies) have been included in the calculation of V_C . Figure 5(a) corresponds to $A = 100$ mV, $f_1 = 500$ Hz and $f_2 = 600$ Hz. The measured spectrum is well reproduced by the analytical model, exhibiting all the spectral components with amplitudes of 6.18 mV for dc, 3.48 mV for $f_2 - f_1$, 12.97 mV for f_1 , 9.95 mV for f_2 , 1.52 mV for $2f_1$, 2.99 mV for $f_1 + f_2$ and 1.47 mV for $2f_2$. The agreement in the time

domain (inset) response is also excellent. Similar results can be observed in figure 5(b) for $f_2 = 50$ Hz.

If we increase the frequency of the excitation, the attenuation introduced by the measuring equipment ($R_{os} C_{cab}$ network) provokes a notable decrease in the amplitude of the harmonics. To avoid it, we have reduced the oscilloscope input impedance to $R_{os} = 100$ k Ω . In this way the characteristic frequency of the pole is raised by a factor of 10 to 60 kHz. The drawback is that now R_{TTJ} is one order of magnitude higher than R_{os} , and so the signal is attenuated by a factor of 11 even at low frequency. In figure 6, corresponding to $f_2 = 19.3$ kHz, these features can be observed. Again we have the different harmonics $2f_1 = 1$ kHz, $f_2 - f_1 = 18.8$ kHz and $f_1 + f_2 = 19.8$ kHz.

Finally, the device has been measured under a higher amplitude of the input signals, $A = 200$ mV, and the results are shown in figure 7 for $f_1 = 500$ Hz and $f_2 = 600$ Hz. In this case, the previously used quadratic expression is not adequate to correctly fit the static V_C - V curve of the TTJ in the whole range covered. So, we propose a higher order polynomial expression such as

$$V_C = A + BV + CV^2 + DV^3 + EV^4. \quad (2)$$

By using this new equation (within the ± 200 mV range) the best fit to the measurements, shown in figure 7(a), is obtained with $A = -0.74$ mV, $B = -0.11$, $C = -6.5$ V $^{-1}$, $D = 4.8$ V $^{-2}$ and $E = 49$ V $^{-3}$. Under these conditions some new harmonics (with respect to the case shown in figure 5(a) for a lower amplitude of the inputs) appear in the spectrum of the output signal, figure 7(b): $2f_2 - f_1 = 400$ Hz and $2f_1 - f_2 = 700$ Hz (V^3 -type response), $2(f_2 - f_1) = 200$ Hz, $3f_2 - f_1 = 900$ Hz, $3f_1 - f_2 = 1300$ Hz, $3f_2 + f_1 = 2100$ Hz, $2(f_1 + f_2) = 2200$ Hz and $3f_1 + f_2 = 2300$ Hz (V^4 -type response). Even if the analytical curve does not show some of the harmonics the agreement is still quite satisfactory, illustrating the almost

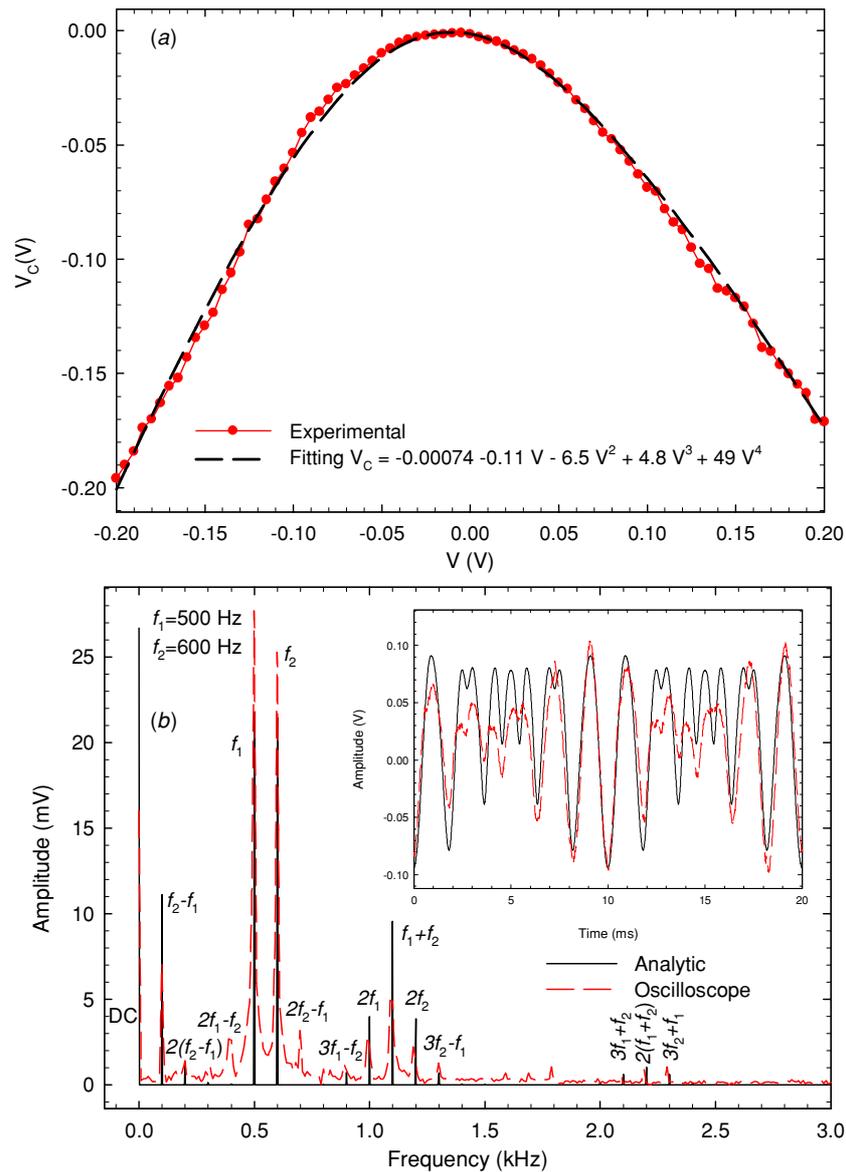


Figure 7. (a) Experimental measurements and analytical fitting for V_C within the ± 200 mV range and (b) frequency and time (inset) domain response of the TTTJ as measured with the oscilloscope and obtained from the analytical model, respectively, for $A = 200$ mV, $f_1 = 500$ Hz and $f_2 = 600$ Hz.

ideal mixing operation of the TTTJ. Remarkably, these results clearly demonstrate that the frequency limitation of the mixing operation is due to the experimental setup; no degradation due to the intrinsic device response is observed (in [9] surface effects were suggested as a source of high-frequency decay of the output).

3.2. Doubling and detection

In this section we report experimental results illustrating the functionalities of TTTJs as frequency doublers and detectors. First, we measure a single Y-shaped TTTJ with 250 nm long and 190 nm wide horizontal branches and 80 nm wide vertical branch with integrated coplanar waveguide accesses, sketched in figure 8(a), whose static V_C - V response is shown in figure 8(b). To characterize the device acting as frequency doubler and phase detector at high frequency, an experimental setup

combining a large signal network analyser (LSNA) with a continuous wave source (Agilent Technologies E8257D PSG) for high-frequency signal generation reaching 20 GHz and coaxial cables for the connections of the source and on-wafer probes is used (more details of the experimental setup can be found in [11]). The measurements are made using high-impedance probes (HIP Picoprobe model 35), with impedance of $1.25 \text{ M}\Omega$, close to the $\text{M}\Omega$ impedance range typical of a TTTJ, thus allowing precise time domain measurements. After adequate calibration steps, the phase and magnitude of the injected (a_1 and a_2) and reflected (b_1 and b_2) waves at the input and output of the device are used to determine the currents and voltages in the frequency or time domain. In figure 8(c) an excellent frequency doubling for an input signal of 4 GHz can be observed: a quasi-sinusoidal signal at 8 GHz is obtained at the output. The spectrum shown in figure 8(d) confirms that the second harmonic is the highest in the output. In order

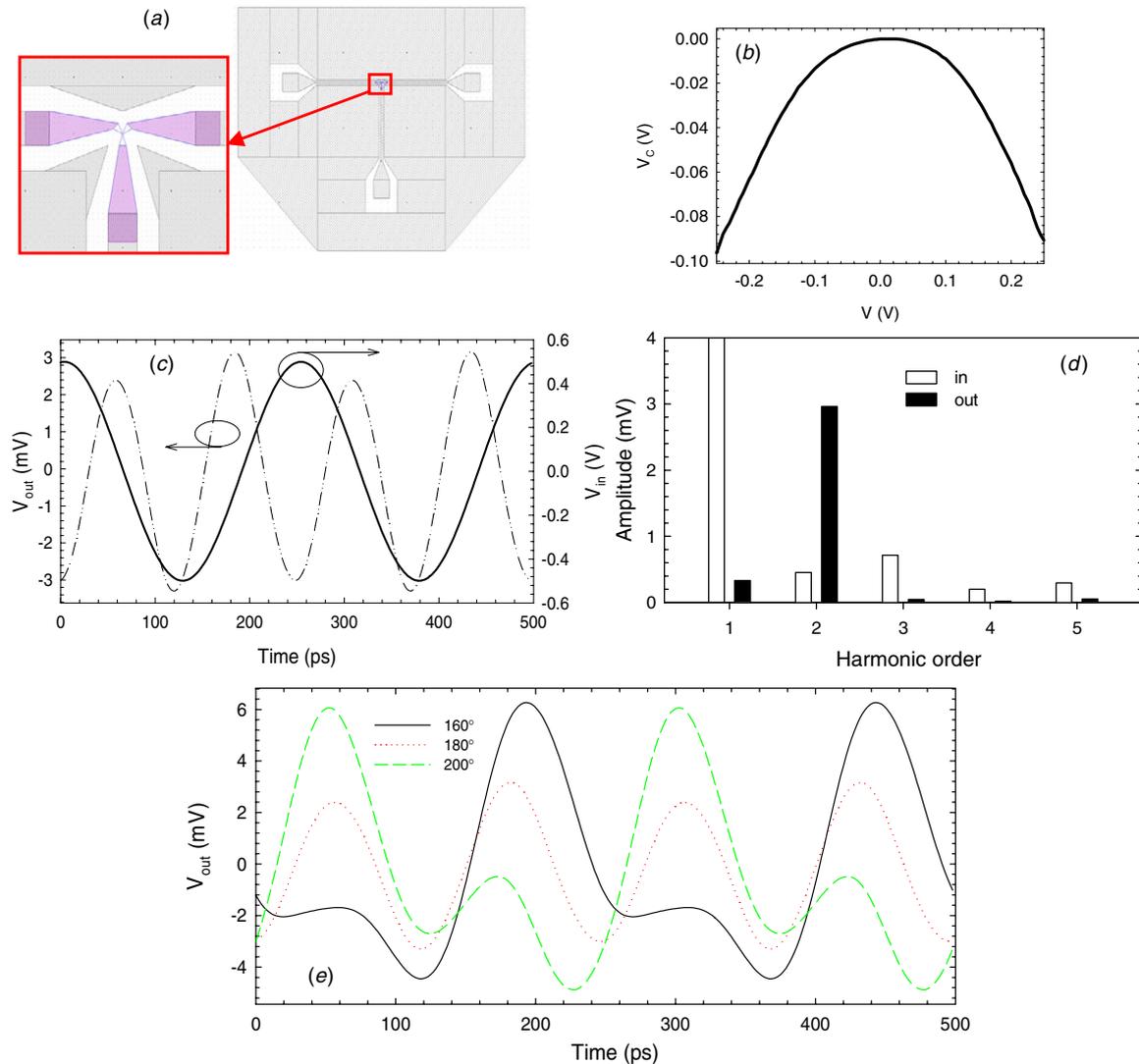


Figure 8. (a) Sketch of the Y-shaped TTI with coplanar wave guide accesses for the measurements and (b) its static V_C - V characteristic. Time domain response obtained with the LSNA at 4 GHz working as (c) frequency doubler with a 5 dBm input signal (its harmonic spectrum is shown in (d)) and (e) phase detector (output for signals with different phase-shifts between inputs).

to check the possibility of phase detection, signals with the same amplitude and three different phase-shifts φ ($V_1 = A\cos(2\pi ft)$ and $V_2 = A\cos(2\pi ft + \varphi)$) have been applied to the right and left branches. The results of these measurements, shown in figure 8(e), are in very good agreement with the theoretical prediction that can be obtained from equation (1).

In the particular case of input power detection, in order to further decrease the input impedance and improve the frequency response of the TTJs, we use a double Y-shaped junction defined by means of reactive ion etching on a typical InP-HEMT epilayer and integrated in parallel in a coplanar waveguide. The width of the stem is 200 nm and the angle between the two 220 nm long horizontal branches is around 60°. The complete frequency characterization of the structure between 3 and 40 GHz was presented in [20]. The setup for the experimental characterization of the RF-dc conversion at 94 GHz is shown in figure 9, where a push-fix input (one branch is biased while the other is grounded [3]) originates a dc component in V_C . Figure 9 shows that the junction is

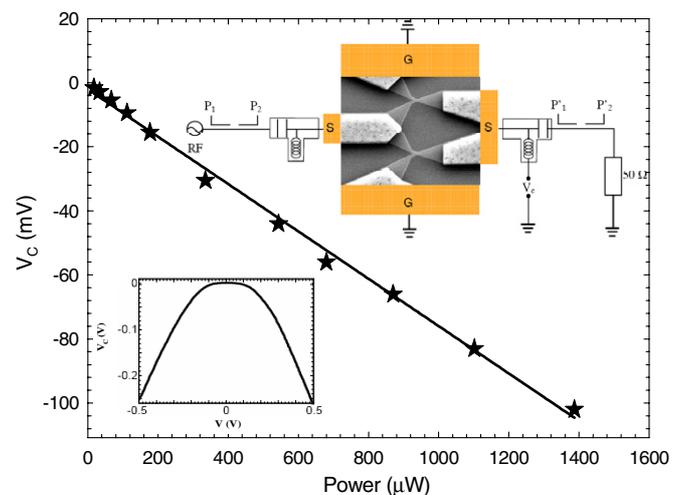


Figure 9. Detected dc value of V_C versus microwave (94 GHz) power injected to the double Y-shaped junction with $V_{\text{bias}} = 0$. The experimental setup used for the measurements and the static results for V_C are shown as insets.

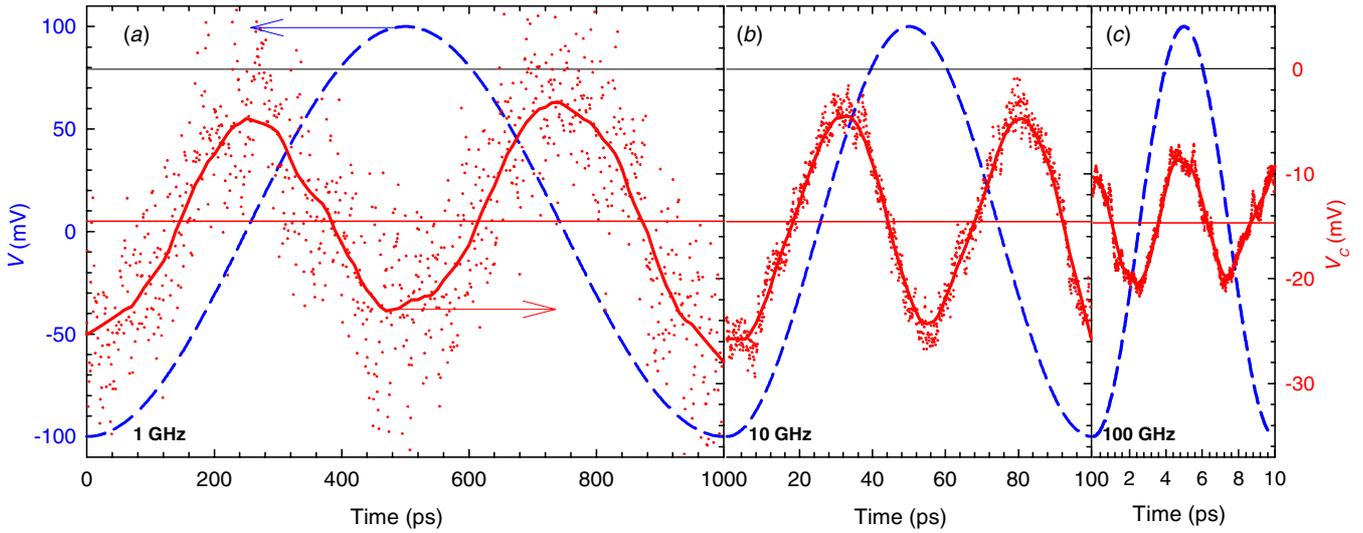


Figure 10. Time domain response of V_C in a T-shaped TTJ to push-pull input signals of amplitude 100 mV and frequency (a) 1 GHz, (b) 10 GHz and (c) 100 GHz. The mean value of V_C (around -15 mV, constant with frequency) is shown as a red horizontal line.

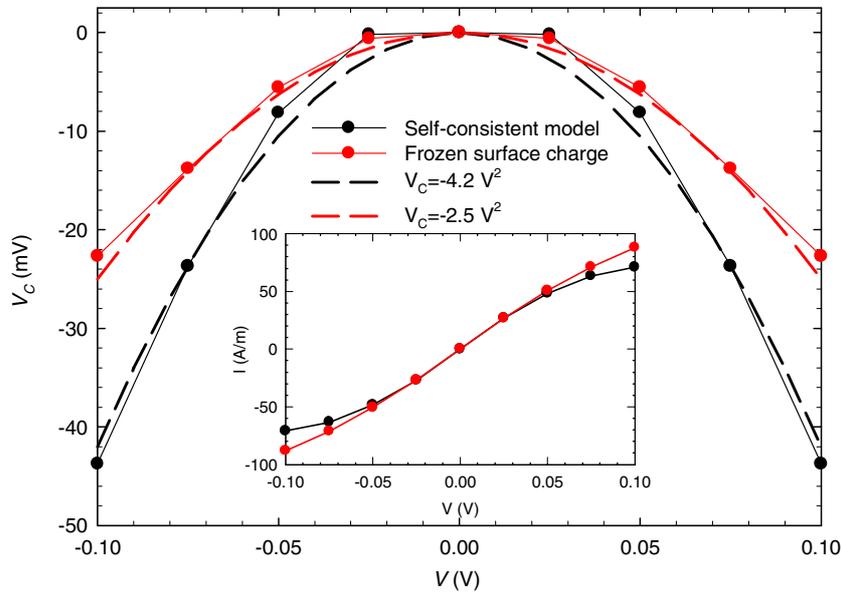


Figure 11. Static V_C - V and I - V (inset) characteristics in the simulated TTJ with two models for the surface charges: the SCCM and frozen surface charge profile calculated under equilibrium conditions. The fitting to a parabolic dependence for the two cases is also represented.

still perfectly operative as a detector at such high frequency, with a measured sensitivity of 76 mV mW^{-1} (without dc bias). The linear dependence is a proof of the square-law dependence of the YBJ output ($V_C = -\alpha V^2$). A real improvement is obtained with respect to 4 mV mW^{-1} at 50 GHz provided by the four-terminal ballistic rectifier [31], and is comparable with 75 mV mW^{-1} obtained with self-switching diodes (SSD) at 110 GHz [32]. However, this sensitivity is still far away from the typical ranges of 4000 mV mW^{-1} at 100 GHz to 400 mV mW^{-1} at 900 GHz of Schottky diode detectors [33].

The main improvement achieved here with respect to previous works [20] is the optimization of the ohmic contact accesses and coplanar waveguide design in order to minimize

extrinsic crosstalk capacitances without excessively increasing access resistances. Poor matching of high-impedance TTJs and the 50Ω equipment is one of the main problems of these ballistic nanodevices. The use of multiple channels is proposed as a solution for improvement of conversion losses [11].

4. Monte Carlo results

As shown in the previous section, the lack of techniques able to test the picosecond response of TTJs restrains us to their study by means of numerical models. First, it is necessary to better understand the underlying physics of the dynamic operation of the devices and, second, to estimate the intrinsic frequency limits that we can expect in ideal conditions. For this purpose

we make use of the MC tool previously described in section 2.2 to simulate, at room temperature, the response of TTJs in the sub-millimetre frequency range.

4.1. Doubling versus detection

The performance of TTJs as frequency doublers or power detectors in the sub-THz range, though not measured experimentally, can be checked (intrinsically) by our MC simulator. To this end, we apply 100 mV sinusoidal signals in push-pull fashion to a T-shaped TTJ with 250 nm long and 120 nm wide horizontal branches and a 60 nm wide vertical branch and calculate the bottom potential V_C output for different excitation frequencies. In figure 10 the time domain evolution of the stem output voltage V_C is represented when the frequency of the input signal is 1, 10 and 100 GHz and the frozen surface charge model is utilized. It can be observed that the device has an excellent performance as a frequency doubler at least up to 100 GHz. The static response of the same device is represented in figure 11. Two models for the surface charge are used here: the self-consistent surface charge model (SSCM) [13] and frozen-to-equilibrium surface charge model [15]. The quadratic fitting for both models are also plotted in the graph. The more negative values obtained from the SSCM are due to the bias re-adaptation of surface charge within this model [18]. From the static behaviour we expect an average output dc value of

$$\overline{V_C} = f \int_0^{1/f} -\alpha[V_0 \cos(2\pi ft)]^2 dt = -\alpha V_0^2/2. \quad (3)$$

For an amplitude V_0 of 100 mV the parabolic fitting of the static response provides an average V_C value of $\overline{V_C} = -12.5$ mV for the simulations with frozen surface charges (using $\alpha = -2.5$ V⁻¹). In figure 10 it can be observed that the time-domain average value obtained with the MC simulations using the frozen model (assuming that the characteristic time of the surface states is much slower than the input signal, in agreement with the results shown in [15]) is in good agreement with this estimation. For input signals of much lower frequencies (when surface charges are able to follow the input), the values obtained for $\overline{V_C}$ would be much more negative (for the SSCM $\alpha = -4.2$ V⁻¹ so that $\overline{V_C} = -21$ mV). In fact, this could be a possibility to experimentally determine their characteristic lifetime, since a low-frequency plateau should be observed, with a cut-off corresponding to the inverse of such time.

For the detailed dynamic study of the TTJs, sinusoidal signals of 0.1 V amplitude are applied to the left and right branches in push-pull fashion, while monitoring the value of V_C . The amplitude of its response, V_{Cac} , informs about the capability of operating the TTJs as frequency doublers, while the average dc value of V_C , $\overline{V_C}$, provides the rectification performance. Both quantities are plotted in dB in figure 12. Due to the quasiballistic motion of electrons within the active region of the TTJ, average velocities as high as 5×10^7 cm s⁻¹ are reached. Therefore, the cut-off frequency of the 560 nm long TTJ presented before should be around 1 THz (associated only with the longitudinal transport). However, while the cut-off frequency of $\overline{V_C}$ is higher than 1 THz, in the case

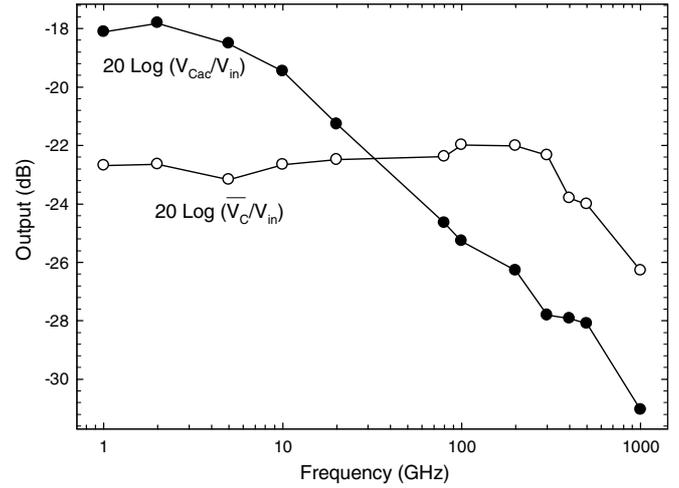


Figure 12. Frequency dependence of the amplitude, V_{Cac} , and the average dc value, $\overline{V_C}$, of the response of V_C (normalized to the input amplitude and in dB) to signals of amplitude 100 mV applied in push-pull to the inputs.

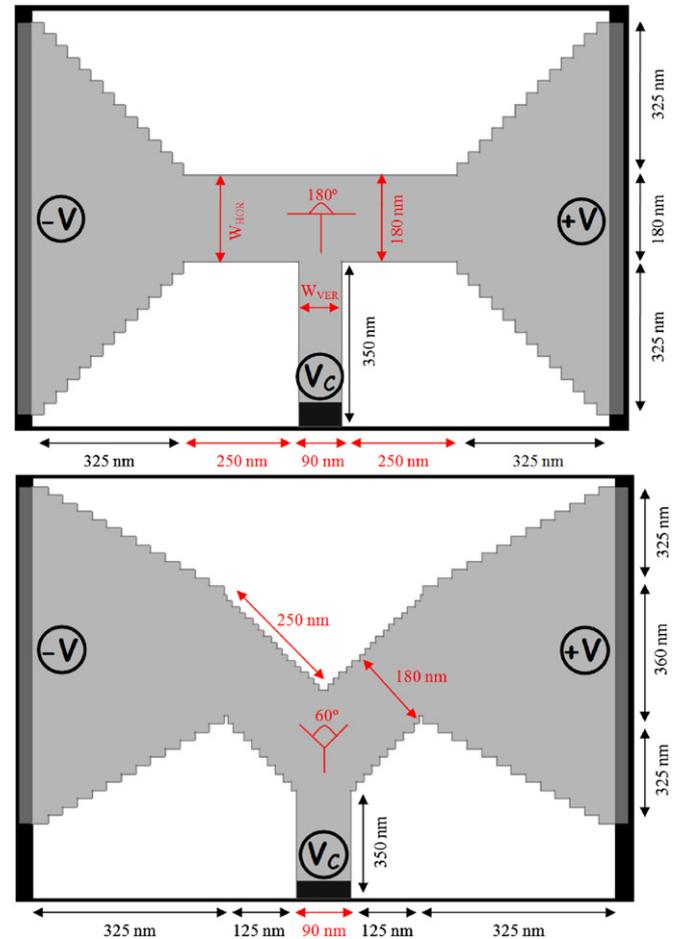


Figure 13. Geometry of the simulated structures. (a) T-shaped junction and (b) Y-shaped junction.

of V_{Cac} the decay appears at much lower frequency, about 50 GHz. This different frequency response appears because rectification (and thus detection) is mainly related to horizontal transport, which is very fast, while the ac amplitude (and thus

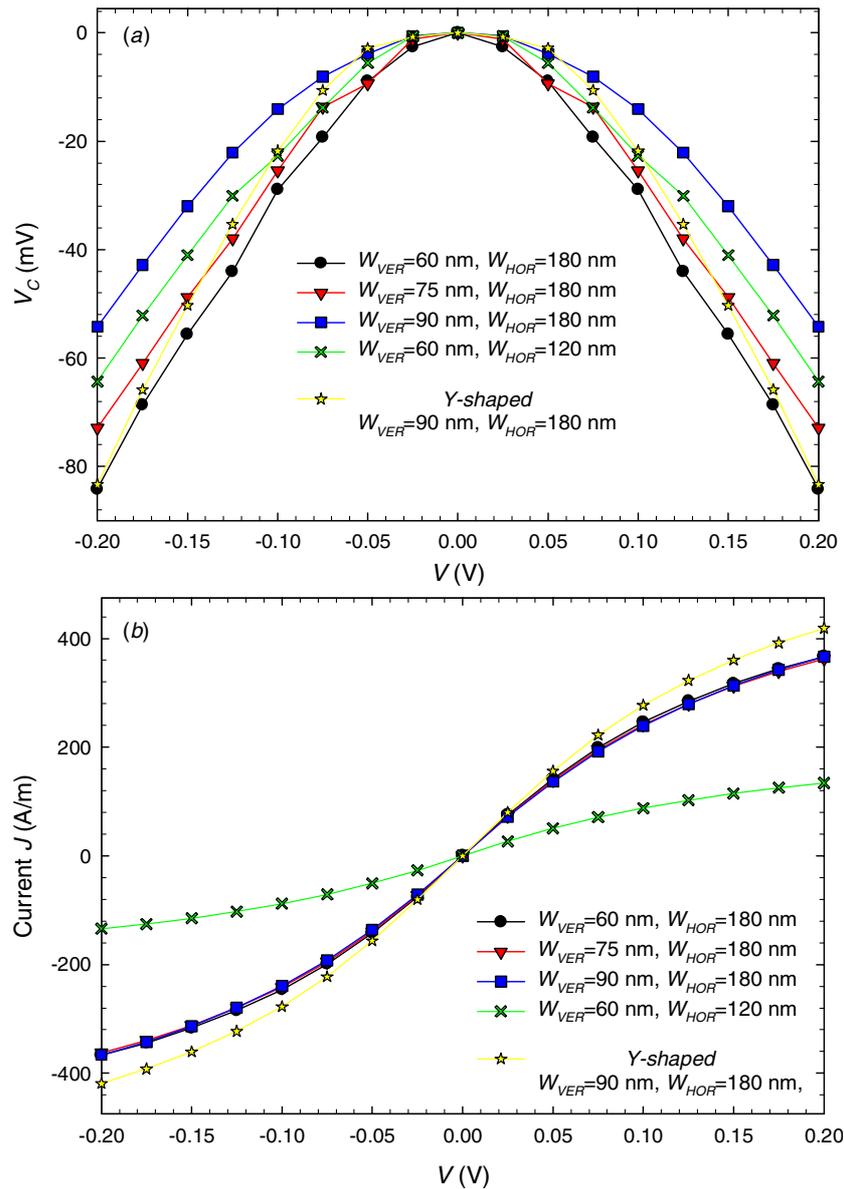


Figure 14. MC values of (a) bottom potential V_C and (b) current as a function of the push-pull bias obtained in T-shaped junctions with different W_{VER} and W_{HOR} and in a Y-shaped junction (shown in figure 13).

frequency doubling) is strongly controlled by the penetration of carriers into the central branch. Since the electric field that forces electrons to enter/leave the vertical branch following the excitation signal is small, the characteristic time of such a process is much longer than the transit time associated with horizontal transport, so that the cut-off frequency for V_{Cac} is much lower than in the case of the dc value. We can double-check this conclusion by studying the dependence of the results on the value of the width of the vertical branch, which we perform in the next section.

4.2. Influence of the geometry: stem width and junction shape

In this section we study the effect of the geometry on the performance of the TTJs. For T-shaped junctions such as the one shown in figure 13(a) we consider two parameters to analyse their influence on the dynamic response: the

width of the horizontal branches W_{HOR} and the width of the vertical stem W_{VER} . Also, we examine the effect of the junction shape by simulating a Y-shaped device, as drawn in figure 13(b).

Figure 14 shows the typical down-bending value of V_C and the current flowing through the horizontal branches in all the simulated junctions. When the width of the vertical branch is reduced, the parabolicity in the bell shape of the V_C - V curves is enhanced, while providing a similar current (as expected since W_{HOR} is the same [13]). A narrower horizontal branch leads to less negative values of V_C (and obviously to lower current). This result is not consistent with the static experimental measurements (shown in [18]), which show more negative values of V_C due to the bias dependence of the surface charge profile. This effect is not considered here, since we focus on the dynamic response of these devices, thus making use of a frozen surface charge profile calculated under

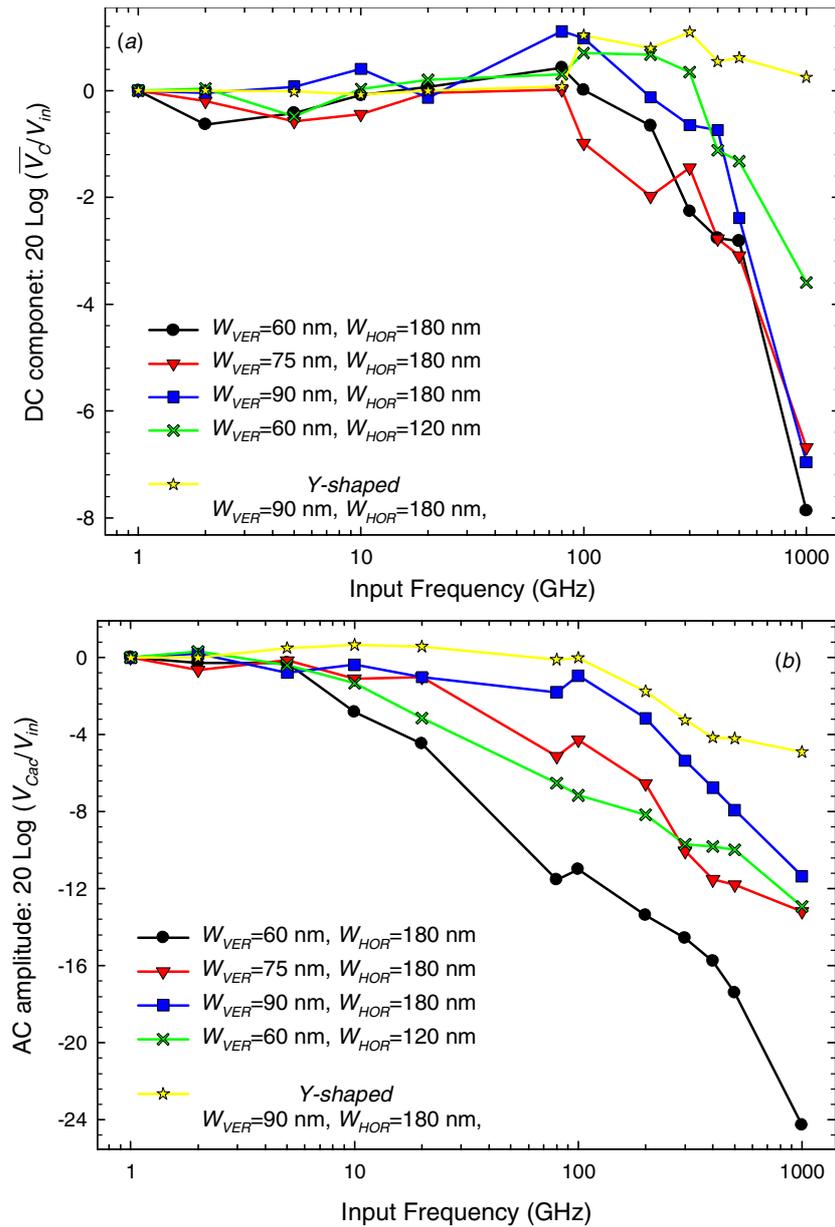


Figure 15. Frequency dependence of (a) amplitude, V_{Cac} , and (b) average dc value, $\overline{V_C}$, of the response of V_C (normalized to the input amplitude and in dB) to signals of amplitude 100 mV applied in push-pull to the inputs in T-shaped junctions with different W_{VER} and W_{HOR} and in a Y-shaped junction (shown in figure 13). For a better comparison, the low-frequency value has been subtracted to each curve.

equilibrium conditions. On the other hand, the stem voltage values are more negative in the Y-shaped junction than in the T-shaped one because of the enhanced electron penetration into the vertical branch [16].

Figure 15 shows the values of V_{Cac} and $\overline{V_C}$ as a function of frequency for the different simulated TTJs (for the sake of clarity the low-frequency value has been subtracted). As a general feature, the cut-off for V_{Cac} , figure 15(b), appears at much lower frequencies than for the mean value, figure 15(a), taking place around 1 THz. As the value of $\overline{V_C}$ is mainly related to the electron horizontal transport, its cut-off is hardly influenced by the width of the vertical branch. On the other hand, V_{Cac} is controlled by the penetration of carriers into the stem, so that its width (W_{VER}) clearly changes its cut-off frequency (higher frequencies for wider stems,

in which carriers enter more easily). Nevertheless, wider stems provide less negative values of V_C at low frequency, as observed in figure 14(a). As a consequence, for an optimized response W_{VER} must be chosen depending on the required type of operation and frequency. On the other hand, when reducing the width of the horizontal branch (W_{HOR}), a slight increase in the cut-off frequency is observed in both quantities; however, the matching to the typical 50 Ω lines would be worse due to the higher impedance of the TTJ. Concerning the shape, the Y geometry much improves the global performance of the device as a result of an enhanced vertical electric field and a stronger injection of carriers into the stem (having a more pronounced influence on the cut-off of V_{Cac} , associated with frequency doubling applications). Moreover, better performances are expected if the angle between left and right

branches of the junction is further decreased. However, if the size of the device is reduced below the Fermi wavelength of the electrons and the temperature is decreased so that the scattering is negligible, the wave nature of the electron transport may come into sight, thus making the sensitivity and cut-off frequency of the TTJs insensitive to the size of the stem channel as well as the angle between the left and right branches [26].

5. Conclusions

In this paper we have experimentally demonstrated the operation of TTJs as mixers, doublers and detectors based on the presence of ballistic or quasiballistic transport. Mixing at low frequency and low amplitude shows an output voltage containing components (apart from dc) at the original input frequencies, and their sum and difference. For higher amplitudes new harmonics appear due to the non-parabolic response of the device. A simple analytical study shows that due to the high value of the TTJ output impedance (of the order of $k\Omega$), considerably larger than the desired value of $50\ \Omega$ of the standard high-frequency experimental equipment, special attention to the impedance matching and cut-off frequency of the measurement setup is essential. For higher frequencies, signal detection up to 94 GHz and frequency doubling and phase detection up to 4 GHz have been experimentally confirmed in a double Y-shaped junction.

By means of MC simulations, we have shown that, at least intrinsically, TTJs are good candidates for building devices capable of operating up to 100 GHz as frequency doublers and even entering the THz range as detectors. The reduction of the stem width increases the sensitivity in the static response but reduces the cut-off frequency for doubling. Nevertheless the detection capabilities are not much deteriorated and a negative value is obtained even for sub-millimetre wave frequencies.

These results show that the robustness of the TTJs' nonlinear response is a unique advantage in terms of realizing room temperature circuits working at ultrahigh frequencies. In order to confirm the theoretical expectations, experimental techniques able to probe the electrical properties of these nanodevices at terahertz frequencies (>100 GHz to 10 THz) are necessary. To this end a promising picosecond electrical measurement setup has been recently proposed [34]. However, aspects related to the fabrication process, reliability and particularly interconnects still have to be investigated in order to use TTJs for room temperature applications that can give us access to the THz range.

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References

- [1] Worschech L, Xu H Q, Forchel A and Samuelson L 2001 Bias-voltage-induced asymmetry in nanoelectronic Y-branches *Appl. Phys. Lett.* **79** 3287
- [2] Shorubalko I, Xu H Q, Maximov I, Omling P, Samuelson L and Seifert W 2001 Nonlinear operation of GaInAs/InP-based three-terminal ballistic junctions *Appl. Phys. Lett.* **79** 1384
- [3] Xu H Q 2002 Diode and transistor behaviors of three-terminal ballistic junctions *Appl. Phys. Lett.* **80** 853
- [4] Mateos J, Vasallo B G, Pardo D, González T, Galloo J S, Roelens Y, Bollaert S and Cappy A 2003 Ballistic nanodevices for terahertz data processing: Monte Carlo simulations *Nanotechnology* **14** 117
- [5] Irie H, Diduck Q, Margala M, Sobolewski R and Feldman M J 2008 Nonlinear characteristics of T-branch junctions: transition from ballistic to diffusive regime *Appl. Phys. Lett.* **93** 053502
- [6] Bollaert S *et al* 2007 Ballistic nano-devices for high frequency applications *Thin Solid Films* **515** 4321
- [7] Lewén R, Maximov I, Shorubalko I, Samuelson L, Thylén L and Xu H Q 2002 High frequency characterization of a GaInAs/InP electronic waveguide T-branch switch *J. Appl. Phys.* **91** 2398
- [8] Xu H Q, Shorubalko I, Wallin D, Maximov I, Omling P, Samuelson L and Seifert W 2004 Novel nanoelectronic triodes and logic devices with TBJs *IEEE Electron Device Lett.* **25** 164
- [9] Worschech L, Reitzenstein S, Hartmann P, Kaiser S, Kamp M and Forchel A 2003 Self-switching of branched multiterminal junctions: a ballistic half-adder *Appl. Phys. Lett.* **83** 2462
- [10] Sun J, Wallin D, Maximov I and Xu H Q 2008 A novel SR latch device realized by integration of three-terminal ballistic junctions in InGaAs/InP *IEEE Electron Device Lett.* **29** 540
- [11] Nakamura T, Kasai S, Shiratori Y and Hashizume T 2009 Fabrication and characterization of a GaAs-based three-terminal nanowire junction device controlled by double Schottky wrap gates *Appl. Phys. Lett.* **90** 102104
- [12] Rahman S F B A, Nakata D, Shiratori Y and Kasai S 2009 Boolean logic gates utilizing GaAs three-branch nanowire junctions controlled by Schottky wrap gates *Japan. J. Appl. Phys.* **48** 06FD01
- [13] Spanheimer D, Müller C R, Heinrich J, Höing S, Worschech L and Forchel A 2009 Power gain up to gigahertz frequencies in three-terminal nanojunctions at room temperature *Appl. Phys. Lett.* **95** 103502
- [14] Sun J, Wallin D, Brusheim P, Maximov I, Wang Z G and Xu H Q 2007 Frequency mixing and phase detection functionalities of three-terminal ballistic junctions *Nanotechnology* **18** 195205
- [15] Vasallo B G, González T, Pardo D and Mateos M 2004 Monte Carlo analysis of four-terminal ballistic rectifiers *Nanotechnology* **15** S250
- [16] Gardès C 2008 Composants nanométriques balistiques de la filière InGaAs/InAlAs/InP pour applications hautes fréquences *Doctoral Thesis L'Université des Sciences et Technologies de Lille*
- [17] Jacoboni C and Lugli P 1989 *The Monte Carlo Method for Semiconductor Device Simulation* (New York: Springer)
- [18] Ñiguez-de-la-Torre I, Mateos J, González T, Pardo D, Galloo J S, Bollaert S, Roelens Y and Cappy A 2007 Influence of the surface charge on the operation of ballistic T-branch junctions: a self-consistent model for Monte Carlo simulations *Semicond. Sci. Technol.* **22** 663

- [19] Sadi T, Dessenne F and Thobel J 2009 Three-dimensional Monte Carlo study of three-terminal junctions based on InGaAs/InAlAs heterostructures *J. Appl. Phys.* **105** 053707
- [20] Sadi T and Thobel J 2009 Analysis of the high-frequency performance of InGaAs/InAlAs nanojunctions using a three-dimensional Monte Carlo simulator *J. Appl. Phys.* **106** 083709
- [21] Mateos J, Vasallo B G, Pardo D, González T, Galloo J S, Bollaert S, Roelens Y and Cappy A 2003 Microscopic modeling of nonlinear transport in ballistic nanodevices *IEEE Trans. Electron Devices* **50** 1897
- [22] Mateos J, Vasallo B G, Pardo D, González T, Pichonat E, Galloo J S, Bollaert S, Roelens Y and Cappy A 2004 Nonlinear effects in T-branch junctions *IEEE Electron Device Lett.* **25** 235
- [23] Iñiguez-de-la-Torre I, González T, Pardo D, Gardès C, Roelens Y, Bollaert S and Mateos J 2009 Influence of the branches width on the nonlinear output characteristics of InAlAs/InGaAs-based three-terminal junctions *J. Appl. Phys.* **105** 094504
- [24] Iñiguez-de-la-Torre I, Mateos J, Pardo D, Song A M and González T 2009 Noise and THz rectification linked by geometry in planar asymmetric nanodiodes *Appl. Phys. Lett.* **94** 093512
- [25] Bednarz L, Rashmi, Hackens B, Farhi G, Bayot V and Huynen I 2005 Broad-band frequency characterization of double Y-branch nanojunction operating as room-temperature RF to DC rectifier *IEEE Trans. Nanotechnol.* **4** 576
- [26] Xu H Q 2001 Electrical properties of three terminal ballistic junctions *Appl. Phys. Lett.* **78** 2064
- [27] Shorubalko I, Xu H Q, Maximov I, Nilsson D, Omling P, Samuelson L and Seifert W 2002 A novel frequency-multiplication device based on three-terminal ballistic junction *IEEE Electron Device Lett.* **23** 377
- [28] Müller C R, Worschech L, Höpfner P, Höfling S and Förchel A 2007 Monolithically integrated logic NOR gate based on GaAs/AlGaAs three-terminal junctions *IEEE Electron Device Lett.* **28** 859
- [29] Wallin D, Shorubalko I, Xu H Q and Cappy A 2006 Nonlinear electrical properties of three-terminal junctions *Appl. Phys. Lett.* **89** 092124
- [30] Cooley J W and Tukey J W 1965 An algorithm for the machine calculation of complex Fourier series *Math. Comput.* **19** 297
- [31] Song A M, Omling P, Samuelson L, Seifert W, Shorubalko I and Zirath H 2001 Operation of InGaAs/InP-based ballistic rectifiers at room temperature and frequencies up to 50 GHz *Japan. J. Appl. Phys.* **40** L909
- [32] Balocco C *et al* 2005 Microwave detection at 110 GHz by nanowires with broken symmetry *Nano Lett.* **5** 1423
- [33] Hesler J L and Crowe T W 2007 Responsivity and noise measurements of zero-bias Schottky diode *Proc. 18th Int. Symp. Space Terahertz Technology* p 89
- [34] Irie H and Sobolewski R 2010 Terahertz electrical response of nanoscale three-branch junctions *J. Appl. Phys.* **107** 084315