Design of a 400 GHz Schottky Mixer for High-Performance Operation

José V. Siles, Jesús Grajal, and Viktor Krozer

***Abstract*— In this work we present the design of a 400 GHz Schottky diode mixer for high performance operation. In order to achieve a proper design a full and joint optimization of both the external circuit and the internal structure of the Schottky diode is performed. Two possible mixer topologies are analyzed: A fundamental mixer and a subharmonically-pumped (SHP) antiparallel diode pair mixer. The advantages and disadvantages of both topologies are discussed. The final results exhibit a single-side band (SSB) conversion loss of 8.6 dB @ 0.4 mW of LO power for the 400 GHz fundamental mixer and 10.3 dB @ 0.8 mW LO power for the 400 GHz SHP mixer, when parasitics are tuned-out. However, if parasitics are not tuned out, an increase in the required LO power is necessary for minimum conversion loss.**

***Index Terms*— CAD, harmonic balance, submillimeter-wave technology, Schottky diode mixers, subharmonically-pumped mixers.**

I. Introduction

This work deals with the design and full optimization of a 400 GHz Schottky diode-based mixer employing a numerical in-house CAD tool that combines an accurate physics-based numerical model of the Schottky diode with an external circuit simulator by means of accurate multi-tone harmonic balance techniques [1]. The diode model incorporates accurate boundary and interface conditions for self-consistent treatment of tunnelling transport, image-force effects and impact ionization. The simulator accounts for limiting mechanisms such as avalanche breakdown, velocity saturation, and increase in the series resistance with the input power. A further description of this CAD tool can be found in [1]- [2].

In order to achieve a high-performance 400 GHz mixer, the optimization of the Schottky mixer performed in this work includes all possible aspects that can be accounted for within the context of mixer design: Input and output matching networks, influence of bias, required LO power, image enhancement, effect of parasitics, mixer sensitivity to input and output mismatches and influence of the Schottky diode characteristics (anode area, length of each layer, doping profile, series resistance, etc.). But all these parameters cannot be individually treated. In this sense, the main advantage of our in-house CAD tool lies on the possibility to perform a joint optimization of both the external circuit and the internal structure of the semiconductor device.

Regarding the topology of the 400 GHz Schottky mixer, two options have been considered and analyzed: A single-diode fundamental mixer and a SHP antiparallel-diode pair mixer. The block diagrams of the analyzed circuits for these two topologies are presented in Fig. 1. Antiparallel-diode pair SHP mixers have the advantage of the current cancelation at even order harmonics and intermodulation products of the LO and RF frequencies. This leads to two important results. On the one hand, the DC current cancelation makes SHP mixers to experiment an important noise reduction in comparison to fundamental mixers [3]. On the other hand, matching networks are much easier to implement as there is no need to take into account the impedances at those frequencies at which current cancelation occurs. However, SHP mixers demand 3 dB more LO power than fundamental mixers and have around 1-2 dB higher conversion losses [4].

A brief comparison between simulations performed with our in-house physics-based numerical CAD tool and measurements from the SHP mixer described in [5] will be also held for validation purposes.

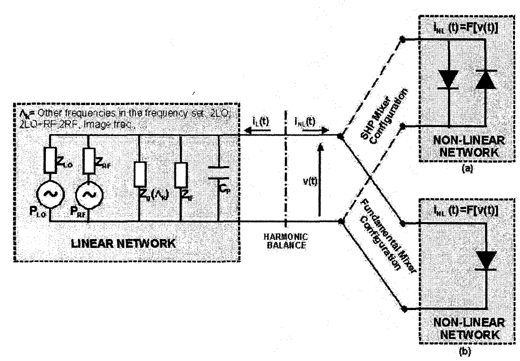

Fig. 1. Block diagram of the analyzed circuit for a SHP antiparallel diode pair (a) and a fundamental Schottky mixer (b).

II. Design of the 400 GHz Fundamental Mixer

It is well-known that the optimization of any of the parameters of a submillimeter-wave Schottky mixers has an influence on the optimum values of the rest of design parameters. Therefore, the joint optimization of them all is required to obtain the highest performance in the final mixer circuit. As the maximum input LO power available is limited to the state-of-the-art solid-state power sources at submillimeter-wave bands, a good methodology of design and optimization might consist of the following: The selection of the optimum bias voltage and epilayer length for each different doping level in order to find the most appropriate set of parameters to get the minimum

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conversion loss. This is because the higher the doping is, the shorter the space charge region of the Schottky diode is and, as a consequence, the optimum bias and epilayer length may vary. Of course, input and output impedances must be optimized as well for all the cases. This task is automatically performed by the design tool at every analyzed LO power.

Fig. 2 shows the influence of the bias voltage in the performance of the 400 GHz Schottky mixer for $2 \cdot 10^{17} cm^{-3}$ doping in the epitaxial layer. It can be depicted that lower LO power levels are required when the bias is increased. The LO and RF impedances are conjugate-matched at each LO power in all the cases unless otherwise specified. The best results are obtained at 0.6 Volts. The effect of the doping level on the conversion loss is presented in Fig. 3. The increase in the doping makes longer the undepleted region of the epilayer so an increase in the LO power is required for minimum loss. There is no velocity saturation effects at 400 GHz, which can be noticed by the fact that the same conversion loss can be obtained with the appropriate LO power in all the cases. Therefore, low dopings $(1 - 2 \cdot 10^{17} cm^{-3})$ are preferred as lower LO levels are necessary to get the best performance.

Furthermore, if the available LO power is fixed in advance, the curve of conversion loss can be shifted towards lower or higher LO powers to place the minimum at the available pump power. This can be done just by modifying the anode area of the Schottky diodes. Hence, a lower LO power will be needed for minimum loss if the area is reduced (Fig. 4). Besides, the change of the anode area modifies the optimum input and output impedance levels that in most of the cases leads to easier-to-built matching networks for lower areas. To exemplify this point, the optimum impedance values predicted by our CAD tool for a $2 \cdot 10^{17} cm^{-3}$ doping at both LO and RF frequencies were $29 + j \cdot 31$ @ A=5 μm^2.

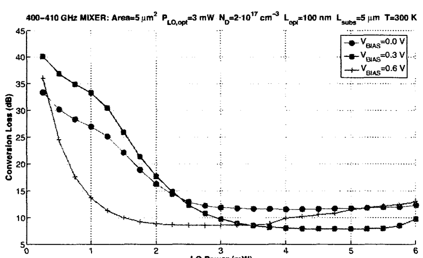

Fig. 2. Influence of bias in the single-side band (SSB) conversion loss of the 400 GHz fundamental mixer at room temperature. No parasitics have been considered (C_p=0 fF). IF optimized at 3 mW LO power.

It is obvious from Figs. 2 to 4 that there is a trade-off among the bias voltage, the doping and the anode area in order to get minimum conversion loss at a certain LO power level.

Another important aspect to be considered in the design process is the influence of parasitics in the mixer circuit. Although these parasitics can be tuned out with proper matching networks, the resultant impedances values required for these networks are usually difficult to synthesize in the practice. As an example, for the 400 GHz fundamental mixer with a 1 μm^2 anode area, the matched LO and RF impedances at 0.5 mW in absence of parasitics are $\sim 140 + j \cdot 150\ \Omega$. For instance, if a 10 fF parasitic capacitance is present in the circuit, the matched LO and RF impedances that tune out this parasitic are $\sim 3 + j \cdot 30\ \Omega$. Fig. 5 shows the effect of the parasitic capacitance in the mixer circuit when it has not been tuned out. The increase in the minimum conversion loss is due to RF input mismatches while the need for higher LO power levels is caused by LO input mismatches.

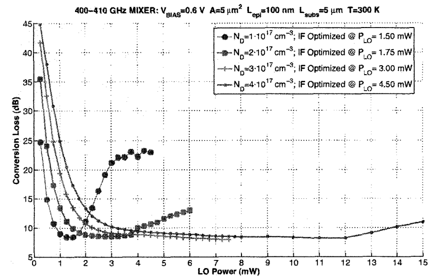

Fig. 3. Influence of epilayer doping in the SSB conversion loss of the 400 GHz fundamental mixer at room temperature. No parasitics have been considered (C_p=0 fF).

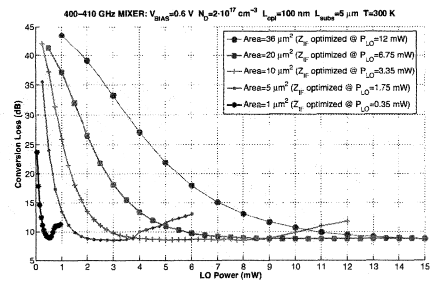

Fig. 4. Influence of anode area in the SSB conversion loss of the 400 GHz fundamental mixer at room temperature. No parasitics have been considered (C_p=0 fF).

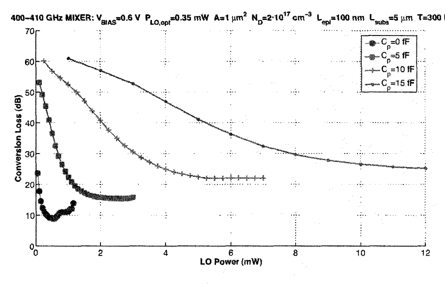

Fig. 5. Influence of the parasitic capacitance in the SSB conversion loss of the 400 GHz fundamental mixer at room temperature. IF optimized at C_p=0 fF and P_{LO}=0.35 mW.

The image enhancement that results of selecting a reactive impedance at the image frequency can be also evaluated by means of our mixer CAD tool. For the 400 GHz fundamental mixer, an improvement of 1.3 dB in the conversion loss has been estimated.

The final results for the 400 GHz fundamental mixer exhibit a SSB conversion loss of 8.6 dB (7.3 dB including the image enhancement). These results corresponds to a 1 μm^2 area, a $2 \cdot 10^{17} cm^{-3}$ epilayer doping and a series resistance R_s =84 Ω. The series resistance is numerically obtained by performing a DC analysis of the Schottky diode with our CAD tool. If the R_s of the Schottky diodes was reduced, for example by shortening the lengths of the its layers, an improvement in the SSB conversion loss will be obtained: 6.0 dB SSB conversion loss when R_s =25 Ω.

III. Design of the 400 GHz SHP Mixer.

The design methodology of the 400 GHz SHP Schottky mixer is analogous to the one employed for the 400 GHz fundamental mixer. Thus, in this section we only present the most relevant results. Fig. 6 shows the influence of the epilayer doping in the performance of the SHP mixer. Again, lower doping levels are preferred at this frequency of operation. The influence of the anode area is also identical to the fundamental mixer case. If the area is divided by a factor 2, the curve of conversion loss shifts 3 dB towards lower LO powers.

It can be noticed in Figs. 6 and 7 that a 3 dB higher LO power is necessary to obtain minimum conversion loss for the SHP mixers as a consequence of using 2 diodes in antiparallel configuration instead a single diode. This also affects to the values of the impedances in the matching networks, which are different from those obtained for the fundamental mixer. This circumstance may sometimes represent an advantage in terms of impedance synthesization. The matched impedances levels when the SHP mixer is driven by the LO power level at which minimum conversion loss occurs are (for a $2 \cdot 10^{17} cm^{-3}$ doping and A=5 μm^2): $Z_{LO} = 20 + j \cdot 45\ \Omega$ and $Z_{RF} = 16 + j \cdot 19\ \Omega$.

The study of the influence of the parasitic capacitance has been omitted here, but the results are similar to those obtained for the 400 GHz fundamental mixer.

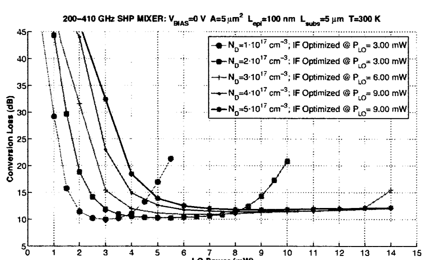

Fig. 6. Influence of epilayer doping in the SSB conversion loss of the 400 GHz SHP mixer at room temperature. No parasitics have been considered (C_P=0 fF)

IV. SHP Mixers Vs. Fundamental Mixers

A comparison between the performances of the 400 GHz fundamental Schottky mixer and the 400 GHz SHP antiparallel-diode pair mixer is provided in Fig. 8.

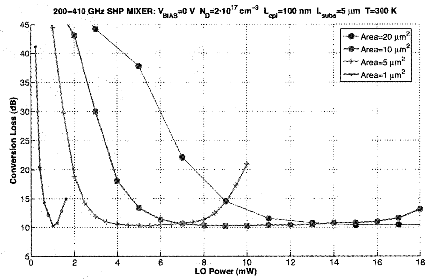

Fig. 7. Influence of anode area in the SSB conversion loss of the 400 GHz SHP mixer at room temperature. No parasitics have been considered (C_P=0 fF)

Althoug the optimum LO power is two times higher in the antiparallel-diode pair SHP mixer, pumping at half the LO frequency of the fundamental mixer may represent and important advantage at these frequency bands because the LO power provided by state-of-the-art solid-state sources decreases with the frequency [6].

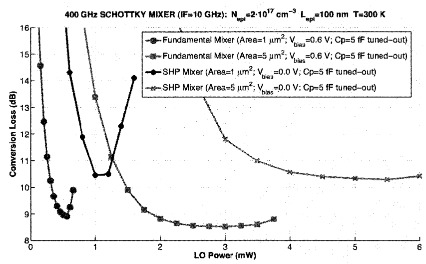

Fig. 8. Comparison between the performances of the 400 GHz fundamental Schottky mixer and the 400 GHz SHP antiparallel-pair Schottky diode mixer.

The minimum SSB conversion loss of the 400 GHz SHP mixer is $\sim$ 1.5 dB worse than in the 400 GHz fundamental mixer, which is in agreement with the literature [4]. However, it is important to realize that a 0.6 V bias has been considered for the fundamental mixer while the SHP mixer has been left unbiased. The absence of bias circuitry makes circuits easier to fabricate, so this advantage must be positive considered in the designs.

Other advantages of the SHP mixer, which are predicted by our CAD tool, are the DC current reduction and the even-order harmonics and intermodulation products current cancellation within the diode pair for antiparallel-diode pair SHP mixers. Furthermore, no implementation efforts need to be made in the circuitry at the even-order frequency components as they do not have influence in the mixer performance. This is corroborated by results in Fig. 9. When all the idler frequencies impedances of the circuit are set to 50 Ω, the conversion loss for the antiparallel-diode pair SHP mixer is not affected with respect to the case in which those impedances are short-circuited. When a single diode SHP mixer is considered a degradation of the performance can be noticed.

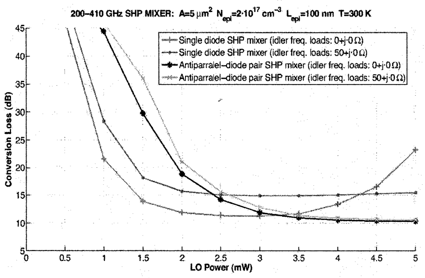

Fig. 9. Comparison between the performances of the 400 GHz fundamental Schottky mixer and the 400 GHz SHP antiparallel-pair Schottky diode mixer. Influence of the impedances at idler frequencies.

V. Validation of the CAD tool

As an initial effort to validate the in-house mixer CAD tool presented in this work, a 330 GHz SHP mixer designed, fabricated and measured in the *Observatoire de Paris* [5], [7], has been simulated using this tool. The Schottky diode employed in the design and fabrication of the mixer is the *SD1T7-D20* from the *University of Virginia*. The characteristics of this diode (provided by the *University of Virginia*) can be found in [7]: An epitaxial layer of 100 nm, an anode area of 0.8 μm^2, an epilayer doping of $2 \cdot 10^{17}$ cm^{-3} ,a built-in potential of 0.72 Volts, a zero junction capacitance of 1.3 fF and a series resistance of 11-15 Ω.

The DC analysis of the diode showed a series resistance of ~ 14 Ω and a 1.3 fF zero junction capacitance C_{j0} that are in good agreement with the nominal values specified by the *University of Virginia.*

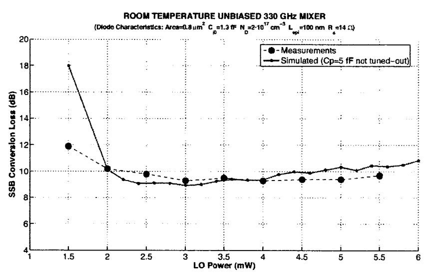

Fig. 10. Comparison between measurements and simulations for a 330 GHz SHP antiparallel-diode pair Schottky mixer [7].

The optimum impedances employed in the simulation were optimized at a 1.5 mW LO power in absence of parasitics: $Z_{RF} = 77 + j \cdot 138$ Ω and $Z_{LO} = 142 + j \cdot 238$ Ω. These values are very close to those considered in [7]: $Z_{RF} = 83 + j \cdot 53$ Ω and $Z_{LO} = 147 + j \cdot 207$ Ω.

A 100 Ω IF output impedance has been considered in both the fabrication and the simulation of the 330 GHz mixer. This value is optimum for the antiparallel-diode pair according to [7], and agrees with the result provided by the IF impedance optimization performed with our CAD tool. The parasitic capacitance of the fabricated mixer is $\sim 5fF$ according to [7]. The optimum impedances if C_p is considered predicted by our CAD tool ($Z_{RF} = 5 + j \cdot 56$ Ω and $Z_{LO} = 4 + j \cdot 120$ Ω) are very different to those employed in the fabrication of the 330 GHz mixer so we have considered that the parasitic capacitance was no tuned out in the results presented in [7]. Taking into account all these considerations, simulations and measurements are in very good agreement as can be depicted from Fig. 10. In order to make possible the comparison, the quasi-optical losses (0.7 dB) and the losses in the IF circuit and SMA connectors (2.5 dB) predicted in [7] have been added to the simulation results. Hence, the final SSB conversion loss is 9.1 dB at 2.4 mW LO power.

If simulations are repeated considering the input impedances that tune out the 5 fF parasitic capacitance, the minimum SSB conversion loss (9.1 dB) occurs at 0.4-0.6 mW instead at 2.4 mW. Anyway, the low values required for the real part of the LO and RF impedances, 4 Ω and 5 Ω respectively, makes extremely difficult the synthesization in practice.

VI. Conclusion

We have presented an in-house CAD tool for the analysis and design of fundamental Schottky mixers and SHP Schottky mixers up to Terahertz frequencies. By means of this tools, a 400 GHz Schottky mixer have been designed and optimized considering the two possible topologies: a fundamental single-diode mixer and a SHP antiparallel-diode pair Schottky mixer. A deep comparison between the advantages and disadvantages of both topologies have been done. The predicted SSB conversion loss are 8.6 dB for the fundamental mixer and 10.3 dB for the SHP mixer. However, these results could be still improved, for example by reducing the series resistance of the diodes.

An initial validation of our CAD tool have been also presented with very good agreement between measurement and simulations of a 330 GHz SHP antiparallel-diode pair Schottky mixer.

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