Effect of idler terminations on the conversion loss for THz Schottky diode harmonic mixers

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***Abstract*—Efficient and reliable frequency converters, preferably operating at room temperature, are critical components for frequency-stabilizing terahertz sources. In this work, we present the analysis of optimum configurations for Schottky diode based x4, x6, and x8 harmonic mixers operating at 2.3 THz, 3.5 THz, and 4.7 THz respectively. Detailed large-signal analysis of the two basic single-ended Z- and Y-mixers was carried out using a standard Schottky-diode model. For each case, the conversion loss was minimized by finding optimal embedding impedances at RF, LO, and IF frequencies. The analysis shows that the Y-mixer has less conversion loss at a low LO pump power. However, the Z-mixer provides reduced loss with increasing harmonic index and pump power due to the associated power dissipation in idler circuits. The results provide preliminary design guidelines for room- temperature frequency converters and their use in phase-locked loop applications.**

Index terms - Harmonic mixers, Phase locking, QCL, Schottky diodes

I. Introduction

Schottky diode based frequency converters offer wide instantaneous bandwidth, low spurious response and high conversion efficiency, thereby a suitable component for phase-locked loop applications. For instance, frequency stabilization of local oscillator sources, e.g. Quantum Cascade Lasers (QCLs), is crucial for high-resolution heterodyne instrumentation at terahertz frequencies. Phase-locking of terahertz sources using microwave component provides highly stable and precise reference frequency and a compact solution, which are important for spaceborne instrumentation. This approach was demonstrated by Betz. et. al [1] and Bulcha et. al using Schottky diode based harmonic mixers [2] and by Hayton et. al using super-lattice diode mixer [3].

Much research has estimated the theoretical limit on conversion loss for fundamental diode mixers [4]. However, less attention has been paid to the harmonic mixers, as conversion loss degrades with increasing harmonic index. The purpose of this ideal simulation study is to analyse the minimum conversion loss that can be obtained for x4, x6, and x8 harmonic mixers with reactive out-of-band frequency terminations [5].

This paper is structured as follows. Section II focuses on the simulation setup in the circuit simulator and comparison of the analytical model with the diode I-V measurement. Section III presents the ideal conversion loss for x4, x6, and x8 harmonic mixers and also the optimum embedding impedance at LO and RF frequencies for two basic mixer topology (Z-, and Y-mixers).

II. Methodology

For the single anode Schottky diode shown in figure 1, we apply an equivalent quasi-static Schottky-diode model, which consists of a non-linear junction capacitance (C_j), a parallel non-linear current source (I-V) and a series resistance (R_s). Extrinsic parasitics and high-frequency effects are excluded [6] and considered to be part of the embedding circuit and the effect of self-heating is not included [7]. For small anode diameters, it is important to add the first-order fringing effect to the junction capacitance model [8]. Series resistance was estimated from the measurement results and FEM simulation. Based on these analytical models, a dc-simulation was setup and figure 1 shows the I-V plot of the in-built diode model with $R_s = 23\,\Omega$, $\eta = 1.2$, $C_{j0} = 0.47\,\text{fF}$ and $I_{sat} = 1\,\text{fA}$, $N_{d,epi} = 5\times10^{17}\,\text{cm}^{-3}$ for $0.15\,\mu\text{m}^2$ anode area.

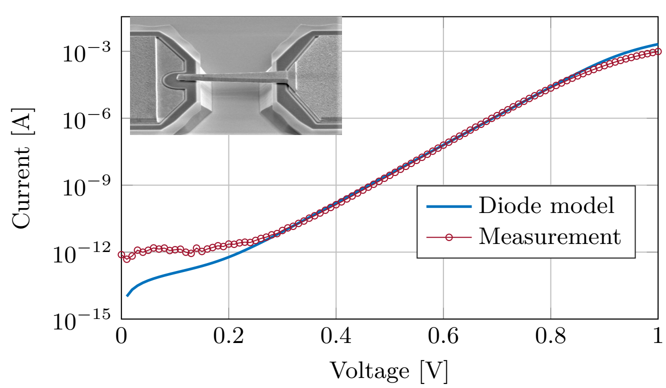

Fig. 1: Measurement and model of the I-V characteristics of an in-house Schottky diode with $0.15\,\mu\text{m}^2$ anode area. The measurement was performed with Kelvin probes at room-temperature (dark condition).

Harmonic balance simulation was performed to study basic single-ended Z- and Y-mixer topologies [5]. Different harmonic mixers (x4, x6, and x8) were studied for a LO frequency of 585 GHz and IF of 10 GHz. The DC-voltage across the diode was kept at zero and all the out-of-band frequencies (idlers) were terminated either as short (Y-mixer) or open (Z-mixer), RF power was set to $-50\,\text{dBm}$. Note at high frequencies, the junction capacitance will be a short therefore it is not a pure Z-mixer [9].

III. Results

Two basic mixer topologies were studied and results are presented in figure 2 for $0.15\,\mu\text{m}^2$ anode area. It can be seen that, for low LO pump power, Y-mixer (short) yields low conversion loss. On the other hand, the Z-mixer (open) gives reduced loss as the pump power increases since there is no power dissipated in the idler circuits. Due to destructive interference between mixing products, conversion nulls are observed in single-ended harmonic diode mixers [10] for Y-mixers as shown in figure 2.

Figure 3 and 4 shows the optimum embedding impedances at LO and RF frequencies respectively that offers minimum conversion loss for Y-, Z-mixer configuration for x4, x6,and x8 harmonic mixers. For low LO power (-20 dBm), the optimum embedding impedances are equal to the small-signal impedance of the diode equivalent circuit. For the x6 harmonic mixer, typical optimum IF impedance is 1200 Ω and 600 Ω for Z- and Y-mixer respectively. Optimum embedding LO and RF impedances for different LO operating power provide useful insights while designing the mixer circuitry.

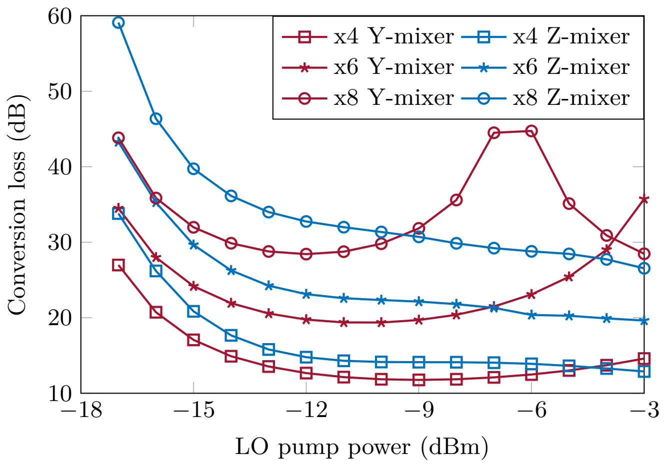

Fig. 2: Conversion loss vs. LO power for 0.15 µm^2 anode contact area for Z- and Y-mixer operating at 585 GHz LO frequency and 2.3 THz, 3.5 THz, and 4.7 THz RF frequency.

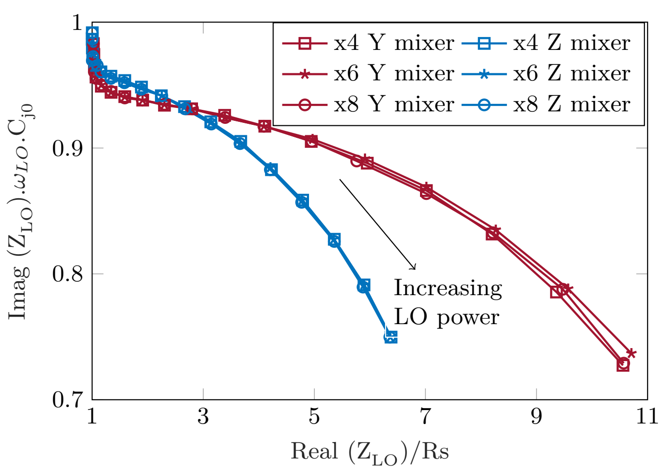

Fig. 3: Optimum LO embedding impedance at 585 GHz plotted for x4, x6, and x8 harmonic mixers in Z-, and Y-mixer configuration in Z-plane for LO power sweep from -20 dBm to -3 dBm. $R_s = 23\,\Omega$ is the diode series resistance and $C_{j0} = 0.47$ fF is the zero-bias junction capacitance.

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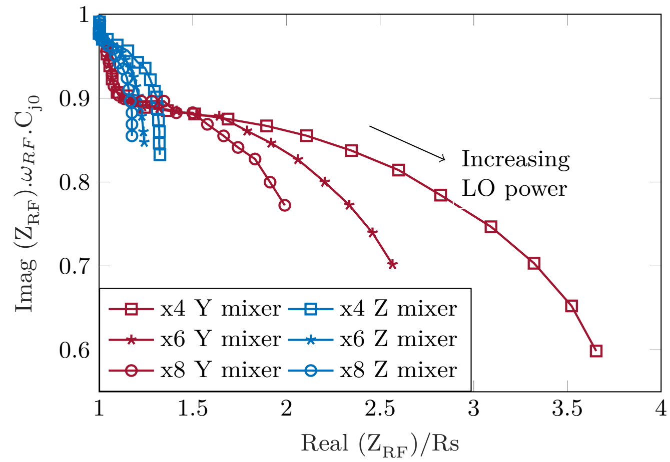

Fig. 4: Optimum embedding RF impedance plotted for x4, x6, and x8 harmonic mixers in Z-, and Y-mixer configuration in Z-plane for LO power sweep from -20 dBm to -3 dBm, $R_s = 23\,\Omega$ and $C_{j0} = 0.47$ fF $\omega_{RF} = n.\omega_{LO} - \omega_{IF}$, where n is the harmonic index.

References

[1] A. L. Betz, R. T. Boreiko, B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Frequency and phase-lock control of a 3 THz quantum cascade laser," *Opt. Lett.*, vol. 30, no. 14, pp. 1837–1839, Jul 2005.

[2] B. T. Bulcha, J. L. Hesler, V. Drakinskiy, J. Stake, A. Valavanis, P. Dean, L. H. Li, and N. S. Barker, "Design and characterization of 1.8–3.2 THz schottky-based harmonic mixers," *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 5, pp. 737–746, Sep. 2016, DOI: 10.1109/TTHZ686.2016.2576.

[3] D. Hayton, A. Khudchencko, D. Pavelyev, J. Hovenier, A. Baryshev, J. Gao, T. Kao, Q. Hu, J. Reno, and V. Vaks, "Phase locking of a 3.4 THz third-order distributed feedback quantum cascade laser using a room-temperature superlattice harmonic mixer," *Applied Physics Letters*, vol. 103, no. 5, 7 2013, DOI: 10.1063/1.4817319.

[4] A. J. Kelly, "Fundamental limits on conversion loss of double sideband resistive mixers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 25, no. 11, pp. 867–869, Nov 1977, DOI: 10.1109/TMTT.1977.1129233,.

[5] A.A.M.Saleh, "Theory of resistive mixers," *MIT press*, 1971.

[6] A. Y. Tang and J. Stake, "Impact of eddy currents and crowding effects on high-frequency losses in planar schottky diodes," *IEEE Transactions on Electron Devices*, vol. 58, no. 10, pp. 3260–3269, Oct 2011, DOI: 10.1109/TED.2011.2160724.

[7] A. Y. Tang, E. Schlecht, R. Lin, G. Chattopadhyay, C. Lee, J. Gill, I. Mehdi, and J. Stake, "Electro-thermal model for multi-anode schottky diode multipliers," *IEEE Transactions on Terahertz Science and Technology*, vol. 2, no. 3, pp. 290–298, May 2012, DOI: 10.1109/TTHZ.2012.2189913,.

[8] J. T. Louhi and A. V. Räisänen, "On the modeling and optimization of Schottky varactor frequency multipliers at submillimeter wavelengths," *IEEE Transactions on Microwave Theory and Techniques*, vol. 43, no. 4, pp. 922–926, 1995.

[9] L. Mania and G. Stracca, "Effects of the diode junction capacitance on the conversion loss of microwave mixers," *IEEE Transactions on Communications*, vol. 22, no. 9, pp. 1428–1435, 1974.

[10] J. Hesler, D. Kurtz, and R. Feinsaugle, "The cause of conversion nulls for single-diode harmonic mixers," *IEEE Microwave and Guided Wave Letters*, vol. 9, no. 12, pp. 532–534, Dec 1999, DOI: 10.1109/75.819422.