COMBINED CIRCUIT-DEVICE TIME DOMAIN SIMULATION OF 2.5 THZ GAAS SCHOTTKY DIODE MIXERS

Haoyue Wang[1], Stephen H. Jones[1], Gregory B. Tait[2], Chris Mann[3]

[1]University of Virginia, Department of Electrical Engineering, Charlottesville, VA 22903
[2]Virginia Commonwealth University, Department of Electrical Engineering, Richmond, VA 23284
[3]Rutherford Appleton Laboratory, Didcot, Oxon, UK

ABSTRACT — In this paper we describe a novel drift-diffusion and time-domain analysis for GaAs Schottky diode mixers operatiing at THz frequencies. The simulator allows for transient analysis and multiple non-commensurate driving tones typical of down-converters.

I. INTRODUCTION

The simulation of THz mixers requires a better understanding of the strong interaction between the nonlinear active device and the linear embedding circuit. As such, mixer numerical simulation techniques must incorporate a combination of a non-linear device simulator and a linear circuit simulator. Simulations should accurately calculate the conversion loss, noise temperature, absorbed and reflected power, device impedances, and time varying current and voltage waveforms, as well as the electron and electric field distributions verses time and position.

In this paper we describe the development of an accurate and efficient simulation tool for THz GaAs Schottky diode mixers. This novel simulation technique incorporates a detailed drift-diffusion device simulator coupled to a time-domain circuit simulator.

II. TIME DOMAIN AND HARMONIC BALANCE METHODS

Traditionally, mixer simulations use harmonic balance techniques to analyze the nonlinear diode embedded in the linear circuit. The diode is typically modeled using a small signal, quasi-static equivalent circuit model. In a harmonic balance circuit simulator (HB) [1], only those frequency components associated with the harmonics of the local oscillator (LO) tone are considered. In the HB frequency domain analysis, only steady-state properties are considered when solving for the device large-signal current and voltage waveforms. Then, small-signal approximations are used to calculate the properties of the down-converted intermediate frequency (IF) signal.

Given the limited frequency components strictly related to the LO, the HB technique is unable to account for complex nonlinear device and circuit interactions during transient conditions. Also, detailed and self-consistent analysis of the current and voltage waveforms cannot be completed using HB since it is impossible to include multiple and non-commensurate frequency signals. At extremely high frequencies one would prefer to use the most complete and detailed analysis of the mixer in order to better understand the complex mixer behavior.

A time domain method (TD) [2] allows for complete transient analysis, the incorporation of multiple and non-commensurate driving tones, and the self-consistent, direct calculation of down-conversion. However, it is computationally intensive and requires efficient implementation to be practical.

Time domain methods are usually convolution based. Unlike HB, where only circuit impedance or admittance is required for the analysis, the time-domain analysis requires the entire embedding circuit frequency response from DC to at least twice the LO frequency. During the simulation the frequency response is converted to the impulse response using the fast Fourier transform (FFT). The convolution of the impulse response and the device current determines the driving terminal voltage, which is then iteratively applied to the device at each time interval. By this process, the diode current and voltage are consistently calculated as functions of time.

Several techniques were proposed to realize the time domain method efficiently [2]. Combined with a drift-diffusion device simulator, this general technique was employed to study transferred electron oscillator (TEO) circuits.

III. DEVICE MODELS AND COMBINED CIRCUIT-DEVICE SIMULATION

Often, the diode can be represented as an equivalent circuit model (EC) of lumped elements [1]. Though simple and fast, an equivalent circuit based code fails to predict proper device performance at high frequencies and drive levels. The model cannot inherently account for phenomena such as current saturation, velocity saturation, and transit time effects. To cope with these difficulties and provide a means for studying the internal physics occurring within the device, more complex drift-diffusion numerical device simulators (DD) and Monte Carlo numerical device simulators (MC) have been incorporated in HB algorithms [3, 4, 6].

The drift-diffusion technique is based on a numerical solution to the first two moments of the Boltzmann transport equation coupled to Poisson's equation [3, 4].

The Monte Carlo technique actually simulates the motion of electrons in both k-space and real space [5, 6]. The Monte Carlo technique offers increased accuracy over the drift-diffusion technique owing to its direct modeling of carrier transport, but suffers lengthy run times and convergence problems.

The three different device simulators have been coupled to harmonic balance methods to simulate complete diode circuits [3, 4, 6].

The numerical ECHB simulation technique developed by Siegel and Kerr is widely used to simulate Schottky diode mixers [1]. First employing a harmonic balance technique, the diode terminal current and voltage waveforms are determined in a large-signal analysis. Then in a small signal analysis, the lumped element values for the equivalent circuit model are extracted, and the conversion loss and noise temperature are calculated.

The DDHB and MCHB codes were developed for Schottky barrier varactor (SBV) frequency multipliers [3, 4, 6].

Both the DDHB and MCHB codes allow for the self-consistent study of device electron transport phenomena and circuit performance. Besides terminal current and voltage waveforms, internal physics are also calculated with excellent computational speed and convergence properties. However, the DD and MC codes have not been implemented in mixer HB simulators to date.

IV. DRIFT DIFFUSION-TIME DOMAIN SIMULATION OF 2.5 THz GAAS SCHOTTKY DIODE MIXERS

The goal of this research is to implement the combined drift-diffusion and time-domain (DDTD) simulation tool for submillimeter wave mixers. At such high frequencies, accurate simulation is very important for the design and optimization of mixers. The task requires the synergistic integration of the drift-diffusion device simulator and the time domain circuit simulator. The DDTD mixer analysis is the first fully self-consistent analysis of high frequency mixers that directly and accurately predicts mixer conversion loss. This analysis will also allow us to observe the electron transport within these devices at high frequencies.

The flow chart of the DDTD code is shown in Fig. 1. The device voltage signal is applied to the DD device model, and the device current signal and internal physics parameters are calculated. A new device voltage is then derived from the TD convolution.

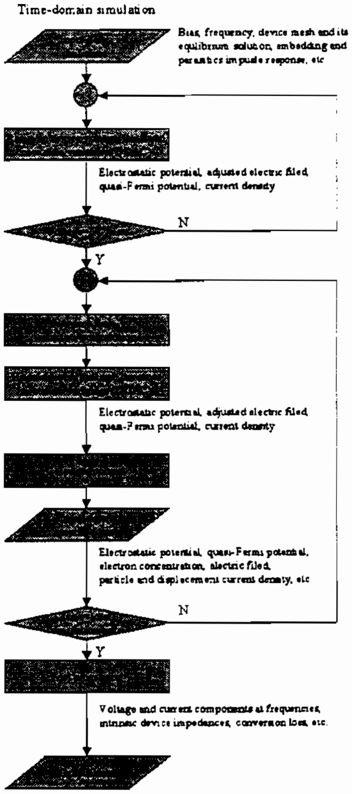


Fig. 1. Flow chart of the DDTD code

The intrinsic device voltage is calculated, via convolution, as

$$V_d(t) = V_{LO}\sin(2\pi f_{LO}t) + V_{RF}\sin(2\pi f_{RF}t)$$
$$-[h_e(t) + h_p(t)] * I_d(t)$$

where $I_d(t)$ is the device current, $h_e(t)$ is the embedding impulse response, $h_p(t)$ is the parasitic impulse response, and V_{LO}, V_{RF}, f_{LO}, and f_{RF} are the LO voltage, RF voltage, LO frequency, and RF frequency, respectively. The equations modeling the device are

$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{q}\frac{\partial J_n(x,t)}{\partial x}$$

$$J_n(x,t) = -q\mu_n(x,t)n(x,t)\frac{\partial \phi_n(x,t)}{\partial x}$$

$$\frac{\partial}{\partial x}[\varepsilon(x)\frac{\partial \psi(x,t)}{\partial x}] = q[n(x,t) - N_D(x)]$$

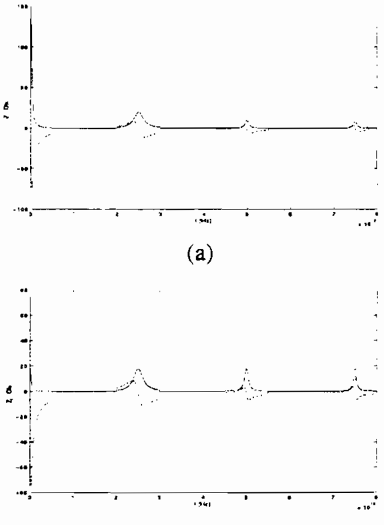
$$n(x,t) = n_{i,ref}\exp[\frac{q}{kT}(\psi(x,t) + V_n(x) - \phi_n(x,t))]$$

where J_n is the electron particle current density, n is the electron density, ϕ_n is the electron quasi-Fermi potential, ψ is the electrostatic potential, k is Boltzmann's constant, q is the electron charge, T is the absolute temperature, $n_{i,ref}$ is the intrinsic electron density in the reference maetrial (GaAs), and V_n, μ_n, ε, and N_D are the alloy potential, electron mobility, dielectric permittivity, and donor impurity concentration, respectively. Combined with the appropriate metal-semiconductor interface and ohmic contact boundary conditions, the carrier transport equations are solved via the coupled-equation Newton-Raphson finite difference technique.

The time step of $V_d(t)$, $I_d(t)$, $h_e(t)$, and $h_p(t)$ should be smaller enough than the LO cycle.

The DDTD code was used to simulate a 2.5 THz Schottky diode mixer incorporating the UVa IT2 GaAs mixer diode [7]. The LO and RF frequencies are 2.511 THz and 2.524 THz, respectively. The diode has parameters of area = 0.28 μm^2, epilayer doping = $5x10^{17}$ cm^{-3}, epilayer thickness = 0.055 μm. The diode is driven by a DC bias voltage of 0.8 V and available LO power of 1 mW and an RF power of 0.4 μW. The time step is 20 fs and much smaller than 1/2.5 THz = 400 fs. The mixer block frequency response has been estimated and is shown in Fig. 2.

Over a relatively long time scale, the entire process from turn-on transient to steady state, as a function of time, is self-consistently and autonomously simulated (Fig. 3). The voltage and current waveforms in a LO cycle are shown in Fig. 4. Sampled uniformly in a LO cycle, electron concentration, electric field, and electron potential energy are calculated to give insight into the internal physics of the device (Fig. 5). By simulating in the time domain, the IF signal is naturally created (see low frequency ripples in the waveform of Fig. 3) and the conversion loss from the incoming frequency to the IF is directly calculated without using any standard small signal analysis. The conversion loss predicted by the DDTD code is 17 dB.



(a)

(b)

Fig. 2 Frequency-dependent impedances (solid: real part, dashed: imaginary part) (a) Embedding impedance. (b) Parasitic impedance.

The time domain method can also be combined with a Monte Carlo algorithm to enable more accurate device modeling.

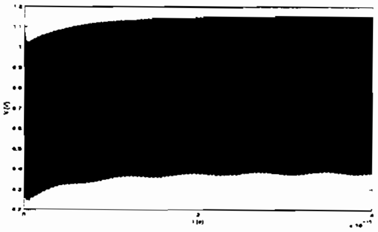
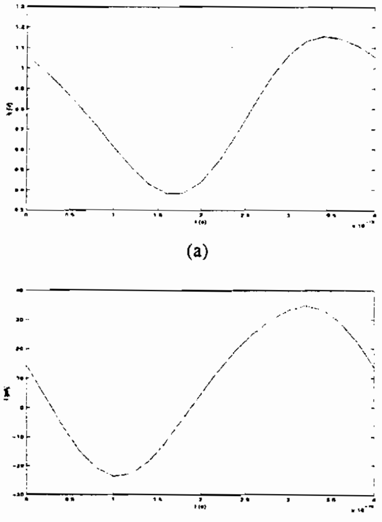


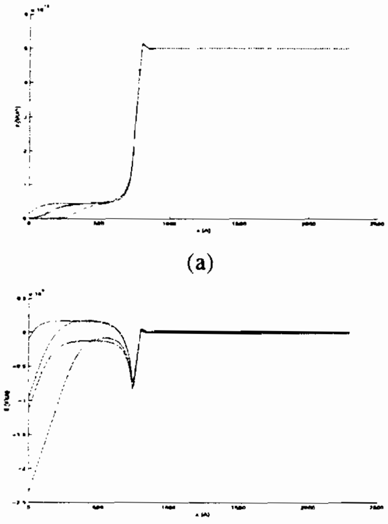
Fig. 3. Device voltage: from turn-on transient to steady state



(a)

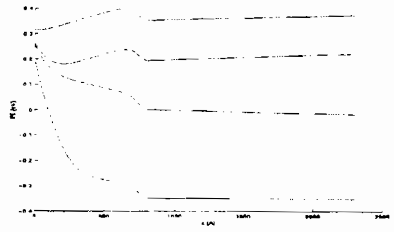
(b)

Fig. 4. Device voltage and current (a) Voltage. (b) Current.



(a)

(b)



(c)

Fig. 5. Snapshots of the internal parameters of the diode. (a). Electron concentration. (b) Electric field. (c) Potential energy.

V. SUMMARY AND CONCLUSIONS

A combined drift-diffusion time domain simulator that allows for transient analysis, the direct calculation of mixer down-conversion, and insight into the internal physics of the device has been demonstrated for the first time. The time domain method can also be combined with a Monte Carlo device model to enable more powerful simulation tools. Continued research is on going to calculate noise temperature and compare simulation results with the actual 2.5 THz mixer.

REFERENCES

[1] P. H. Siegel, A. R. Kerr, and W. Hwang, "Topics in the Optimization of Millimeter-Wave Mixers," *NASA Tech. Papers*, No. 2287, March 1984.

[2] G. B. Tait and S. H. Jones, "Transient Simulation of Harmonic TEO Circuits," *Proc. Ninth Int. Symp. Space Terahertz Technol.*, March 1998.

[3] J. R. Jones, S. H. Jones, and G. B. Tait, "Self-Consistent Physics Based Numerical Device/Harmonic-Balance Circuit Analysis of Heterostructure Barrier and Schottky Barrier Varactors Including Thermal Effects," *Proc. Sixth Int. Symp.*

Space Terahertz Technol., March 1995, pp. 423-441.

[4] L.F. Horvath, J. R. Jones, S. H. Jones, and G. B. Tait, "Numerical Device/Harmonic-Balance Circuit Analysis of Schottky Barrier Varactors," *Proc. 1995 Int. Dev. Research Symp.*, Vol. 1, Dec. 1995, pp. 259-262.

[5] U. V. Bhapkar, "Monte-Carlo Simulation of GaAs Schottky Diodes for Terahertz Frequencies," Doctoral Dissertation, University of Virginia, 1995.

[6] R. E. Lipsey, "Computer Aided Design of Schottky Barrier Varactor Frequency Multipliers," Master's Thesis, University of Virginia, May 1997.

[7] C. M. Mann, D. N. Matheson, B. N. Ellison, M. L. Oldfield, B. P. Moyna, J. J. Spencer, D. S. Wilsher, and B. J. Maddison, "On The Design And Measurement of a 2.5 THz Waveguide Mixer," *Proc. Ninth Int. Symp. Space Terahertz Technol.*, March 1998.