Efficient Simulation of Millimeter-Wave IMPATT Oscillators by FATE, a Combined Time- and Frequency-Domain Method

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Abstract—**The FATE method for the determination of the periodic steady state in oscillators proposed recently [1] is shown to be ideally suited for the simulation of oscillators with strongly nonlinear active devices, e.g., IMPATT oscillators. Simulations of a waveguide oscillator illustrate the choice of a favorable network partition and the advantage of the bandwidth-unlimited time-domain simulation of the nonlinear subnetwork. A *V*-band hybrid-integrated IMPATT oscillator is simulated with agreement in output power within 4 dB over the dc current range from 100 mA to 220 mA compared to the measured levels and a time-domain simulation.**

I. Introduction

The FATE method (frequency and time-domain evaluation of an oscillator's periodic steady state) has been proposed in [1] to meet the conflict between the requirement of a network approximation by concentrated elements in time-domain simulations and the difficulty to account for strong nonlinearities in frequency-domain approaches like harmonic balance.

Both of these problems are very critical in IMPATT oscillators and have hampered a wide-spread application of large-signal multifrequency simulation for these devices. Due to the strong nonlinearity of the IMPATT diode, frequency conversion coefficients within the diode are large (see e.g., [2], [3]) and an *a priori* bandwidth limitation in the simulation is not justified. As impedance levels at higher harmonics of a millimeter-wave resonator are difficult to reproduce, the oscillator's sensitivity to higher harmonic signal levels is an important criterium for the rejection of a bad design.

On the other hand, the diode housing usually has a low pass character, so that harmonic signal levels in the resonator are very low. The numerical effort of frequency-domain approaches concerning memory and CPU time requirements rises stronger than linearly with the number of harmonics considered. So a simulation method where the bandwidth restriction in the resonator does not imply the neglect of the effect of higher harmonic signals on the fundamental is highly desirable.

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II. Application of FATE to a Waveguide IMPATT Oscillator

The FATE method requires the division of the oscillator network into a nonlinear part, treated in the time-domain, and a linear part, treated in the frequency-domain. The *W*-band waveguide oscillator presented in [4] can be separated as shown in Fig. 1. First, the network is divided at the diode terminals. There is only one port connecting the subnetworks, so the interaction between nonlinear and linear subnetwork is completely characterized by the port voltage u_D and the port current i_D. The port current is chosen as the source term ($l_1 = \vec{l}$ in [1], as the port source vector is one-dimensional in this case) and u_D constitutes the response term ($c_1 = \vec{c}$ in [1]). The nonlinear subnetwork is described by a set of first-order ordinary differential equations in the state variables $\vec{x}^T = (u_D, i_c, i_{e1}, d_{e2}, i_e)$:

$$\frac{du_D}{dt} = \frac{1}{C_D(u_D)}(I_0 - i_e - i_D) \tag{1}$$

$$\frac{di_c}{dt} = \frac{2v_s}{w_a}\left[\left(\int \bar{\alpha}(u_D, i_c)\, dx - 1\right) i_c + I_s\right] \tag{2}$$

$$\frac{di_{e1}}{dt} = \frac{1}{\tau_1(u_D)}(i_c - i_{e1}) \tag{3}$$

$$\frac{dd_{e2}}{dt} = \frac{2k}{\tau_2(u_D)}\frac{di_c}{dt} - \frac{2}{\tau_2(u_D)} d_{e2} - \frac{1}{\tau_2^2(u_D)}(i_e - i_{e1}) \tag{4}$$

$$\frac{di_e}{dt} = \frac{di_{e1}}{dt} + d_{e2}, \tag{5}$$

with

i_c	avalanche current
i_e	current at the diode terminals influenced by the drift process
i_{e1}, d_{e2}	auxiliary variables for the modeling of the drift process [5], [6]
C_D	capacity of the space charge layer
τ_1, τ_2	time constants for the modeling of the drift process,

representing a modified Read model incorporating space

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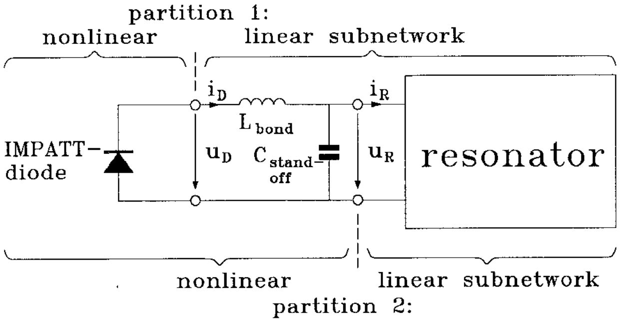

Fig. 1. Network separation of a waveguide IMPATT oscillator.

charge effects and diffusion. The impedance of the resonator is calculated by mode matching [7], [8].

Unlike harmonic balance, the FATE method implies no bandwidth limitation in the nonlinear subnetwork. The diode housing acts as a low pass, so that the signals in the resonator can be well approximated by sinusoids. In this case, it is favorable to include the diode housing part in the nonlinear subnetwork adding two differential equations

$$\frac{di_D}{dt} = \frac{1}{L_B}(u_D - u_Q) \tag{6}$$

$$\frac{du_Q}{dt} = \frac{1}{C_Q}(i_D - i_R) \tag{7}$$

to this system, and the two state variables i_D, u_Q to the state vector $\vec{x}$. Now i_R is the port source exiting the subnetworks and u_Q is the response term used to find the periodic steady state characterized by equal responses from the nonlinear and linear subnetwork. Fig. 2 illustrates the effect of the different ways to divide the network: For an equally close matching of the response term, partition 1 (see Fig. 1) requires the assumption of three harmonics in the source i_D, while partition 2 requires only the fundamental frequency in i_R. This reduces the numerical effort by a factor of 2 to 5 s on an IBM 320 workstation. Even if the spectrum of the port source current i_R is restricted to the fundamental, the internal diode signals simulated by the FATE method will exhibit a high harmonic content. As an example the avalanche current i_c is shown in Fig. 3. This current cannot be measured at the waveguide output, but its harmonics have critical influence on the diode's impedance level at the fundamental frequency. The spectrum of the avalanche current is nearly independent of the number of harmonics considered at the port connecting the subnetworks. Thus the fast processes within the semiconductor are mainly due to up- and downconversion by the diode's nonlinearity and not by harmonic interaction of diode and resonator. This justifies the neglect of higher harmonics at the port.

III. Simulation of a Hybrid-Integrated IMPATT Oscillator

Experimental data [9] and time-domain simulation results have been published previously, along with the equations of the time domain model [6]. As the FATE method accepts the description of the linear subnetwork in the frequency-domain, the effect of the network approximation used in the

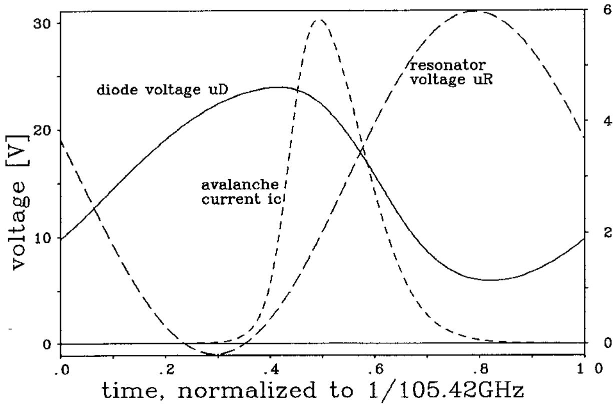

Fig. 2. Time dependence of u_D, u_R and i_c in the case of a sinusoidal excitation in i_R; time is normalized with respect to the oscillation frequency $f_0 = 105.42$ GHz.

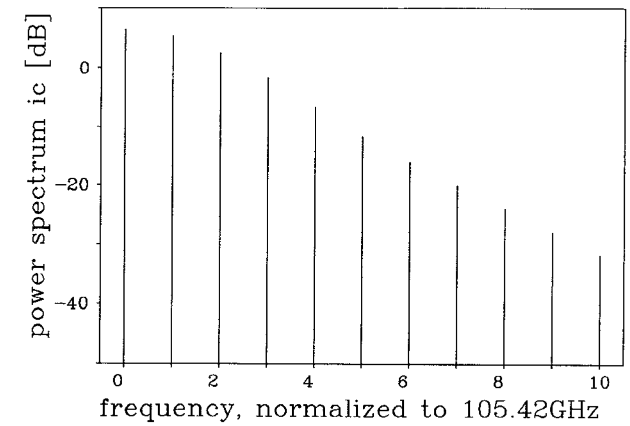

Fig. 3. Power spectrum of i_c in the case of a sinusoidal excitation in i_R; the frequency is normalized to 105.42 GHz.

time domain simulation can be determined. Fig. 4 contains a comparison between the measured output power and the corresponding simulation results for a time-domain simulation and two simulations with the FATE method, one with the network approximation used in the time-domain, the other with the resonator impedance given by Buechler [10]. If the network approximation is used, the output power at small dc currents is lower because of the lower Q factor of the approximation [6]. The high power levels obtained in the FATE simulation are quite realistic, since the simulated power levels contain the power dissipated in the resonator. These losses have been estimated by Buechler to be about one half of the total power dissipated (private communication). The main difference between the time-domain simulation and the FATE results is that the time-domain simulation predicts a quasiperiodic oscillation for dc current densities above 10 kA/cm^2. The fact that FATE converges to a periodic result indicates that a small parameter change, namely an open circuit for the higher harmonics neglected at the port, will lead to a periodic oscillation. The oscillation frequency predicted by FATE still differs by 5 GHz compared to the measured 70 GHz, which may be caused by small errors in the assumptions used for the impedance calculation, since the impedance variation is rather weak near the oscillation frequency [6].

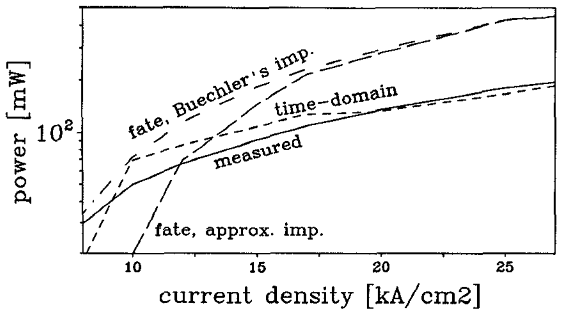

Fig. 4. Comparison in measured and simulated output power of the hybrid-integrated oscillator; the current at the diode terminals is chosen as the port source with three harmonics; the diode area is $8 \cdot 10^{-6}$ cm^2.

IV. Conclusion

While time-domain simulations have advantages in terms of full generality of the stationary state occuring in an oscillator, and harmonic balance is fastest in the simulation of weakly nonlinear periodic or quasiperiodic systems, the FATE method is advantageous in applications including strongly nonlinear devices (e.g., varactor diodes and bipolar transistors) and distributed and/or high Q circuits. In this case, the combination of nearly unlimited bandwidth in the time-domain integration of the nonlinear network part and the signal representation by truncated Fourier series in the linear network part is advantageous. An example for that has been given by the simulation of IMPATT oscillators in this letter.

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