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Design and Optimization of Millimeter–Wave IMPATT Oscillators Using a Consistent Model for Active and Passive Circuit Parts

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Abstract

A new CAD approach for analysis, development, and optimization of millimeter–wave oscillator circuits is presented. The method has been developed with respect to universality, accuracy, and efficiency regarding the consistent modelling of active two–terminal devices operating in passive circuits. Some benefits of the approach are demonstrated by a number of results for practically realized Si and GaAs CW IMPATT oscillators at 94 and 140 GHz. It is likely that millimeter–wave IMPATT diodes operate often in a subharmonic mode in which the fundamental power may or may not be reduced compared to a single–frequency excitation.

1. Introduction

The design of millimeter–wave oscillators involves both the active device and the passive circuit. Since stable operation points are characterized by matched impedances between source and load, the main tasks are the determination of dynamic device impedances and the construction of passive circuits offering appropriate impedances at the frequencies of interest.

Usually, the active device is assumed to be driven by a sinusoidal voltage, and corresponding dynamic impedances can easily be calculated for a single–frequency excitation. However, this assumption is invalid under certain circumstances occurring in practical systems, e. g., harmonic or sub–harmonic operation (whether being intended or not). In these cases, the matching behavior of the complete circuit may significantly deviate from what is expected following the device data obtained as described before.

This problem can be overcome by a consistent treatment of the active device and the passive circuit. However, such an approach requires a substantial effort regarding the development of accurate but nevertheless numerically efficient mathematical models for semiconductor devices with short active regions (showing nonstationary carrier transport) and a suitable description of the passive network which should be applicable to different circuit types. Hence, only little work regarding this topic is available (e. g., [1], [2]).

2. Models for active device and passive load

In the present work, an extended bipolar hydrodynamic model is used that covers all effects of nonstationary transport. All relevant physical processes such as thermal generation, impact ionization, and tunneling are included, so that many important two-terminal devices such as Gunn-, PIN-, IMPATT-, BARITT-, and MITATT-devices can be examined. Special attention has been paid to the inclusion of the thermal energy and diffusive heat flux since these parameters may have a significant effect on the performance of unipolar devices. Furthermore, two additional energy balance equations for accurate modeling of impact ionization are included, allowing Monte-Carlo generated data for ionization coefficients to be used. In contrast to other models, the present one closely reproduces measured breakdown and DC operating voltages. Complete device structures (including very highly doped contact regions) are considered without any simplifications. The system of partial differential equations is solved by a full-implicit, decoupled algorithm. A special discretization of Poisson's equation causes unconditional stability of the whole solution procedure and allows large time steps compared to ordinary schemes to be used. The temperature rise across the semiconductor layers mounted on copper or diamond heat sinks is calculated separately, and appropriate sets of Monte-Carlo generated transport data are used.

The impedance calculation for waveguide mounting structures is a very complex task. The present analysis is restricted to widely used circuits consisting of either a radial line formed by a disc and a post in a rectangular waveguide of full height or a post in a reduced-height waveguide. The load characteristic as seen at the semiconductor device package plane is calculated by well-known mode-matching techniques [3], [4]. The impedance transformation caused by the device package and a series loss resistance is taken into account. It will be shown how suitable values for the parasitics can be extracted with the help of the mode-matching technique. A very good quantitative description even over broad frequency bands is then achievable. Furthermore, the influence of the bias choke can be consistently included in a modified program version [4].

The load impedance is given as a table of frequency-dependent values. A purely time-domain scheme for the inclusion of the interaction of the active device and the load impedance has been developed which is easy to implement and is well suited for highly nonlinear, broad-band circuits where harmonic balance methods might suffer from convergence problems. The impulse response of the load admittance is obtained from an inverse FFT (with typically 2^{15} - 2^{18} values). The convolution of this function with the time-dependent input signal gives the output response of the passive network in each time step which is used in turn to update the driving force for the active device. After a steady state is reached, the result is examined by means of Fourier analysis. Due to generally low quality factors of order 50 - 100 of the networks, stable operation points are reached in a few ns or less in most cases. Compared to the time needed for the semiconductor calculation itself, the convolution method increases the computation time only by several ten percent. Hence, overall computation times are mainly dictated by the space and time increments which have to be chosen smaller as the doping level increases. Compared to unipolar devices, computation times for bipolar devices are approx. one up to one-half order higher and vary from seconds to hours on modern RISC workstations (HP 9000/700), while typical times are some minutes for a single operation point of an IMPATT oscillator.

3. Results

Gunn and IMPATT oscillators operating in W– and D–bands have been intensively studied. A number of results for Si and GaAs IMPATT devices mounted in different circuit configurations will be presented. An important conclusion is that millimeter-wave IMPATT–diodes are usually working in a subharmonic mode with a power component at $f_0/2$. Matching at this frequency is possible because it lies typically below the avalanche frequency where the circuit impedance is capacitive. In this multifrequency operation, dynamic impedances may differ from results obtained by the usually assumed single–frequency excitation with a sinusoidal voltage. The maximum available output power at f_0 may or may not be significantly effected; no clear tendency has been found. However, compared to power losses due to subharmonic components, ohmic losses dominate at small device areas. The additional power components are absorbed by series loads such as contact or skin resistances of a few tenth of an Ohm. Since this power below the cutoff frequency does not leave the resonator and is quite small, it is usually not measured or even detected.

A particularly interesting application of the method is a sensitivity analysis around an operating point. This is useful for optimization of a circuit in order to get the maximum power from the active device. As an example, a 94 GHz IMPATT oscillator described in [5] has been modelled in detail, including package parasitics and an ohmic loss resistance of 0.35 Ω. It uses a disc–type resonator in a WR10 waveguide. Some typical results for varying mount geometries are given in Figs. 1 – 3. The operating point represents the maximum observed power output of approx. 300 – 320 mW at 95 GHz. These drawings clearly demonstrate the strong influence of disc and post diameter upon frequency and output power. However, the disc thickness mainly affects the frequency. Hence, if an oscillator has been built and optimized with respect to the output power level but its operating frequency has still to be fine tuned, another disc thickness can be chosen without affecting the power significantly.

4. Conclusion

A new simulation tool for the design and optimization of millimeter–wave oscillators is presented. A number of different semiconductor devices as well as all commonly used resonator configurations can be modeled. Consistent simulations of practically realized oscillators show a good qualitative and quantitative agreement.

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5. Figures

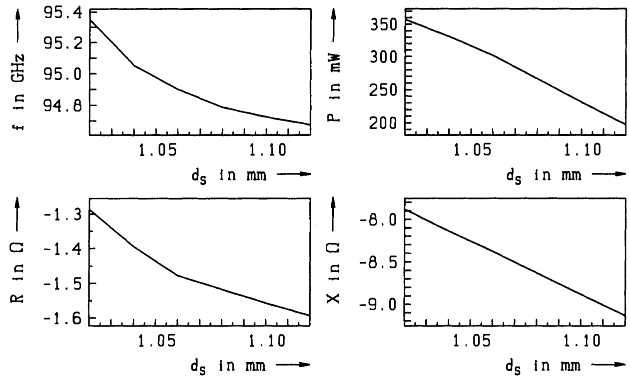

Figure 1: Operating frequency, output power, dynamic resistance and dynamic reactance vs. disc diameter.

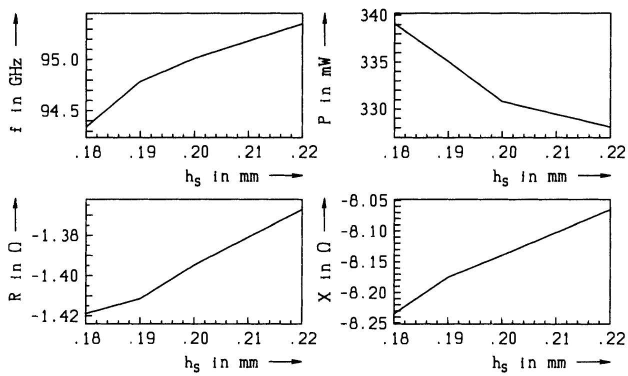

Figure 2: Operating frequency, output power, dynamic resistance and dynamic reactance vs. disc thickness.

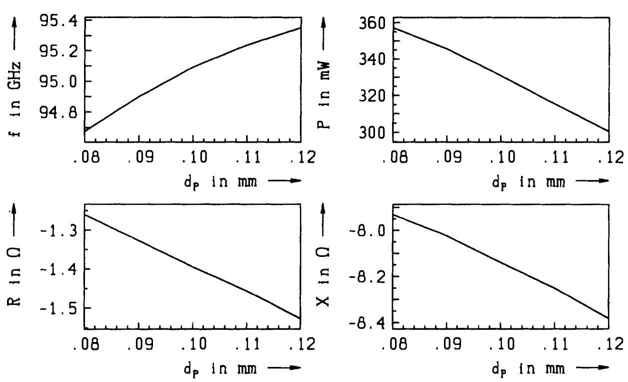

Figure 3: Operating frequency, output power, dynamic resistance and dynamic reactance vs. post diameter.