DESIGN AND OPTIMIZATION OF MILLIMETER-WAVE IMPATT OSCILLATORS

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Abstract

An efficient frequency–domain nonlinear circuit analysis for the design of IMPATT oscillators is presented. A nonlinear circuit model for the active device which is valid up to millimeter–wave frequencies is combined with the load impedance function of a radial–line resonator waveguide mount calculated by mode–matching. Results for a 140 GHz GaAs IMPATT diode oscillator demonstrate that the method is well suited to investigate the influence of resonator dimensions and parasitic elements on the oscillator performance systematically.

Introduction

For the design of millimeter–wave oscillators, different approaches using time–domain or frequency–domain techniques and various kinds of active device models have been investigated. However, accurate modeling of the semiconductor device by Monte Carlo (MC) methods is time–consuming and the incorporation into a complete simulation tool for oscillator design is still impractical. On the other hand, the performance of a realized oscillator not only depends on the characteristics of the active device, but also on various parameters like parasitic elements and the dimensions of the passive circuit. For an efficient design, one has to investigate the influence of these parameters in order to get optimum operation.

In this contribution, a method for the design of IMPATT oscillators is introduced which has been developed in order to fulfill the requirements mentioned above. Furthermore, the method is suitable for the analysis of noise and synchronization properties, as well as the analysis of more complex structures like power combiners. The model for the active device, the passive load structure, and their implementation are briefly described. Finally, some results are given for a 140 GHz oscillator.

Active device model

For the design of semiconductor devices in the millimeter–wave region, hydrodynamic models (HDM) and Monte Carlo (MC) methods are used succesfully. However, the main drawback of these methods is the large computational effort, especially when diode design has been finished and complete oscillator circuits or even a more complex system are to be analyzed.

The IMPATT diode model used here has been derived in [1] and applied in [2], [3]. In comparison with [4], physical effects in the semiconductor are described more accurately since diffusion and a distributed drift region model are taken into account. However, the model of [1] becomes invalid at millimeter–wave frequencies, as nonstationary carrier transport effects get increased significance. For that reason, the avalanche region equivalent circuit has been extended empirically by nonlinear elements $R_a(|V_a|,\omega)$ and $C_a(|V_a|,\omega)$ as shown in Fig. 1. The functional dependency of both elements in-

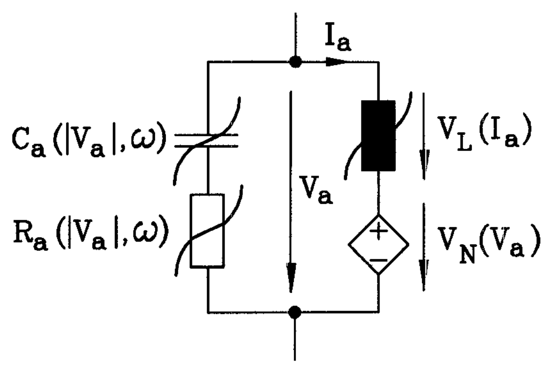

Fig. 1: Modified circuit model of the avalanche region utilizing a nonlinear avalanche capacitance C_a and a nonlinear avalanche resistance R_a.

cludes some constants, whose determination proceeds as follows: For a given diode structure, the impedance characteristic is calculated for an impressed DC current

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by HDM simulation [6] versus both frequency and impressed AC voltage V_1. Best fit to the HDM reference results determines these constants. From the nonlinear circuit model, the diode impedance is evaluated by a frequency–domain power series approach [2], [5].
In Figs. 2 and 3, small– and large–signal impedances of the present model are compared with HDM [6] and standard drift–diffusion model (DDM) results for a 140 GHz GaAs double–drift Read structure [7].

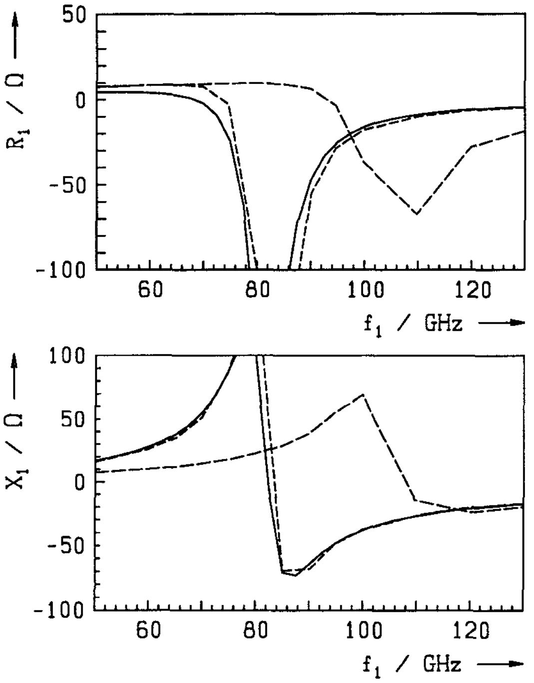

Fig. 2: Comparison of small–signal impedance for a 140 GHz GaAs double–Read structure [7]. Present model (———), DDM (— — —), HDM (- - - -) [6]. $J_{DC} = 80\text{kA/cm}^2$.

Resonator model

For the realization of millimeter-wave IMPATT oscillators, two rectangular waveguide mounting structures are preferred, namely inductive–post and disc–cap resonators. The present analysis focuses only on the latter type which is shown in Fig. 4. The determination of the driving–point impedance at the semiconductor device package plane by mode–matching technique has been described in [8], [9] where good agreement between theory and experimental results has been demonstrated. In the present analysis, the program MARGARET [9] has been used for the impedance calculations.
Furthermore, parasitic elements have important influence on oscillator performance since they cause impedance transformation and losses. These effects are taken into account by a series resistance R_s (bulk and contact losses, as well as skin effect losses), a series inductance L_s (connecting leads), and a parallel capacitance C_p (quartz stand–off) as depicted in Fig. 5. Even though the description of the parasitics by lumped elements is only a coarse approximation, it is suitable to investigate their influence on the oscillator performance systematically. It should be noted that a more general approach for resonator and package modeling can be performed by three–dimensional field analysis tools like HFSS of HP [10]. However, such simulators suffer from their large computational effort.

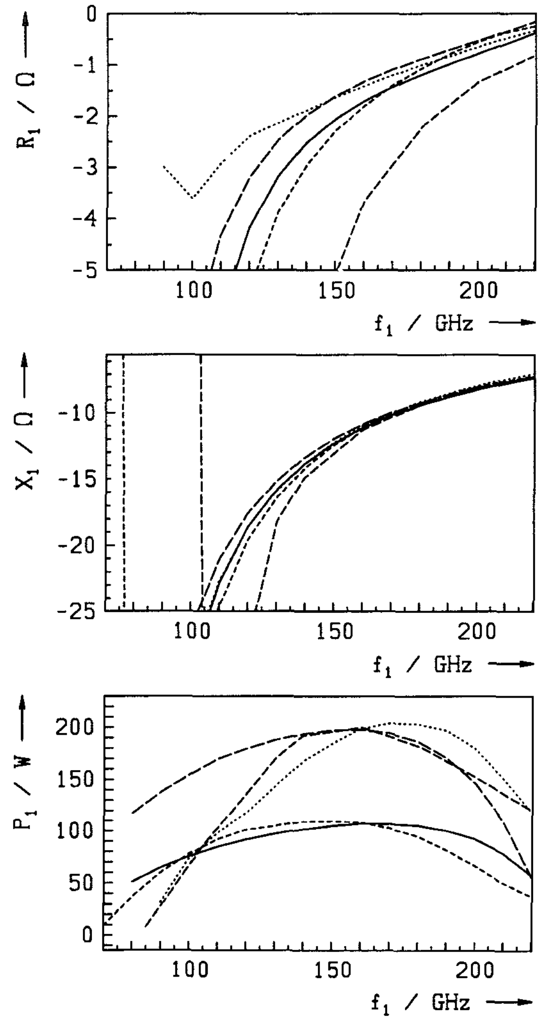

Fig. 3: Comparison of large–signal impedance and output power for the diode of Fig. 2.
V_1 = 4V: Present Model (———), DDM (— — — —), HDM (- - - - - -) [6].
V_1 = 6V: Present Model (— — —),q HDM (······) [6]. $J_{DC} = 80\text{kA/cm}^2$.

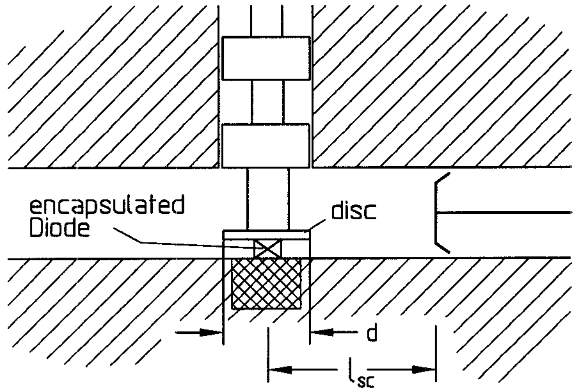

Fig. 4: Cross section of a disc–cap resonator waveguide mount.

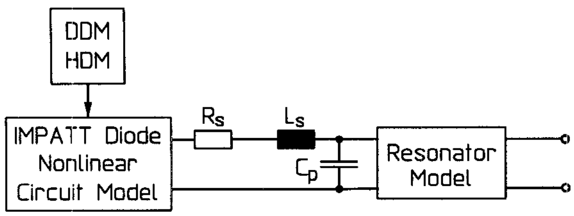

Fig. 5: CAD circuit of the oscillator.

Oscillator analysis

Possible operating points are determined by the condition $\sum_i Z_{D,i}(\omega_i, V_i) + Z_{C,i}(\omega_i) = 0$ where $Z_{D,i}$ and $Z_{C,i}$ denote diode– and circuit impedance of one spectral component at frequency ω_i. In the present analysis, only single frequency operation has to be considered as oscillation at higher harmonics will not occur due to the strongly increasing reactance of the load impedance for higher frequencies. For a given set of parasitic elements and resonator dimensions, operating points are found by an optimization routine [2]. In comparison with the time–domain method [6], only a tiny fraction of computation time is consumed. Thus, through a variation of resonator parameters, as well as parasitic elements, optimum design can be achieved systematically. In Fig. 6, a comparison between the present method and a HDM time–domain approach [6] is shown for a D–band oscillator (diode design from [7]). Satisfactory agreement for both frequency and output power versus sliding short position l_{sc} is demonstrated. Note that both methods use the same load impedance function, as well as the same parasitic elements. Fig. 7 shows the influence of varying disc diameters on oscillation frequency and output power.

The influence of ohmic losses due to contact and bulk resistances is depicted in Fig. 8. Obviously, these losses are the main output power limiting factor in practical circuits as the maximum output power is degraded by a factor of five for a realistic specific contact resistance of $R_s = 3.5 \cdot 10^{-6}$ Ωcm^2 for ohmic contacts. Furthermore, the analysis of a 94 GHz oscillator has been compared with measurements.

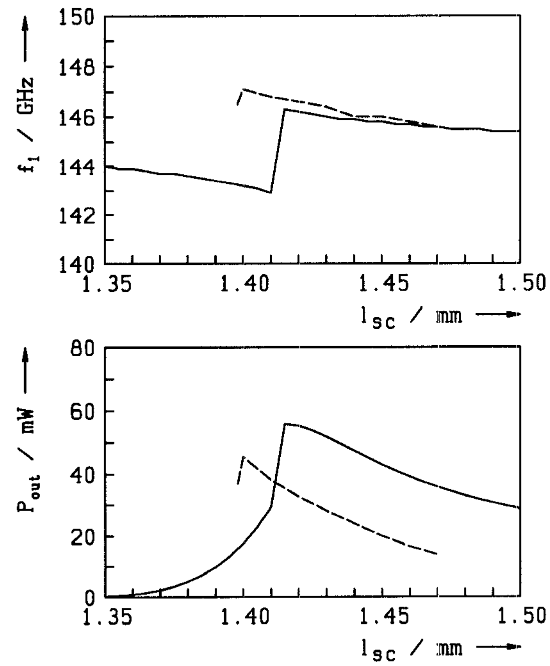

Fig. 6: Frequency and output power of a 140 GHz IMPATT oscillator versus sliding short position. Present method (———), time–domain simulation [6] (— — —).

Conclusions

A method for the design and optimization of millimeter–wave IMPATT oscillators is introduced. A modified nonlinear circuit model is matched to the results of a hydrodynamic model (HDM) and combined with waveguide disc-cap resonator analysis. Thus, the diode model includes nonstationary transport effects empirically. Due to the small computational effort, the influence of resonator parameters on the oscillator performance can be investigated systematically. The method has been applied to the analysis of a D–band IMPATT oscillator succesfully.

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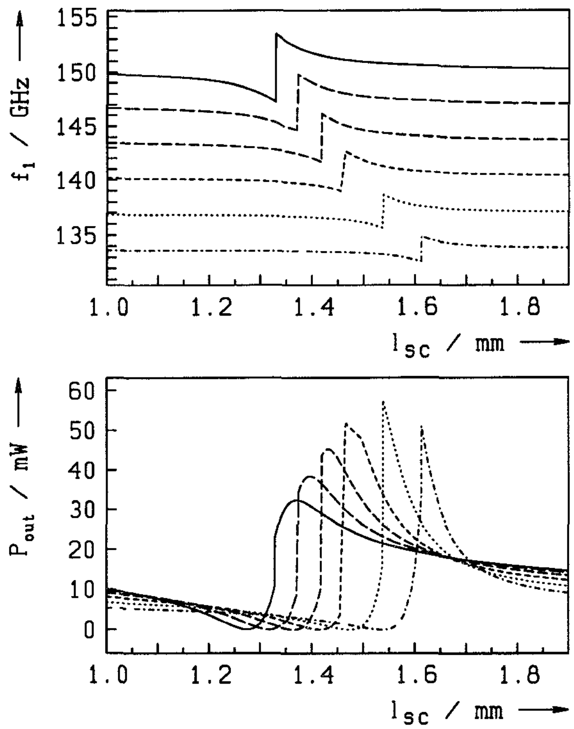

Fig. 7: Frequency and output power of a 140 GHz IMPATT oscillator versus sliding short position for different disc diameter. d = 0.64 (———), 0.68 (— — —), 0.72 (– – – –), 0.76 (- - - - - -), 0.80 (······) and 0.84 mm (- · - · -). R_s = 1.5 Ω, L_s = 13 pH and C_p = 0.15 pF.

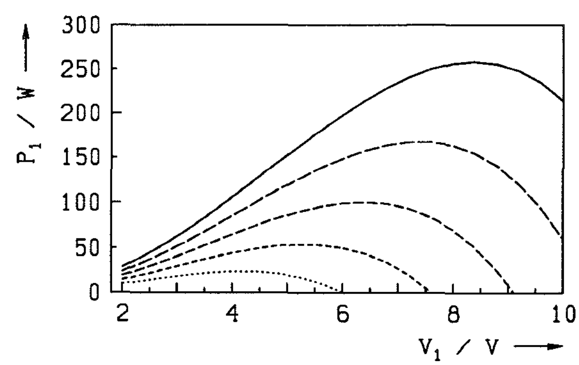

Fig. 8: Degradation of max. output power of a 140 GHz GaAs double-Read diode [7] versus impressed voltage V_1 for different series resistances R_s. R_s = 0.0 (———), 0.4 (— — —), 0.8 (– – – –), 1.2 (- - - - - -) and 1.6 Ω (·······). f = 150 GHz, J_{DC} = 80kA/cm^2.

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