A NEW APPROACH IN CAD OF MM-WAVE IMPATT OSCILLATORS

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ABSTRACT

A computer synthesis of a waveguide CW IMPATT oscillator is presented. The oscillator design is treated as an impedance-matching problem, using a non-isothermal drift-diffusion model for the IMPATT diode. An optimum design of a passive circuit is described, together with a new technique for calculating the output power-oscillating frequency dependence. Comparison with experimental results gives good agreement at W-band frequencies (75-110 GHz).

INTRODUCTION

This paper introduces a new approach to the computer-aided design of CW waveguide IMPATT oscillators. Previous millimetre-wave oscillator models reported in the literature either rely on small-signal device models [1],[2], and therefore cannot yield output power, or use non-linear device equivalent circuit models [3], accompained by a number of simplifications and assumptions, which may limit their accuracy. These methods are also unsuitable for investigating the influence of device structure and its physical parameters on oscillator characteristics. This is faciliated by a time-domain model of an IMPATT oscillator reported by T.Goeller and F.X.Kaertner [4]. They described the dymanics of an oscillator by a set of first-order differential equations (using approximations based on device physics), and an elementary circuit model is used so that the study of circuit behaviour, such as oscillator tuning as a function of waveguide short position or other circuit parameters, is impossible.

This paper describes an improved time-domain physical model of avalanche diodes, which is based on a non-isothermal static drift-diffusion approximation. The oscillator cavity is represented by a first-order equivalent circuit. The oscillator design is carried out in the frequency-domain [5]. A passive-circuit synthesis method and a new way of calculating the dependence of the output power upon frequency of oscillation are presented. Theoretical and experimental results are compared and good agreement is observed at W-band frequencies.

OSCILLATOR MODEL

A large number of self-consistent large-signal numerical algorithms for avalanche diode simulation based either on classical [6-8], or semi-classical methods [9,10] have been reported. Semi-classical methods are more detailed but less efficient and sometimes even less accurate [10]. It has been suggested that classical methods are of sufficient accuracy at frequencies well above 100 GHz [11].

The standard set of semiconductor equations usually does not include the heat flow equation [6-11]. Thermal effects are taken into account through the concept of the diode thermal resistance. However, a more consistent and accurate approach is to include the heat conduction equation directly into model. The basic set of semiconductor equations is given below:

$$\frac{\partial n}{\partial t} = -\frac{1}{e}\frac{\partial J_n}{\partial x} + g \tag{1}$$

$$\frac{\partial p}{\partial t} = \frac{1}{e}\frac{\partial J_p}{\partial x} + g \tag{2}$$

$$\frac{\partial E}{\partial x} = \frac{e}{\varepsilon}(N + p - n) \tag{3}$$

$$\nabla \cdot k \nabla T + Q = 0 \tag{4}$$

where n and p are electron and hole densities, J_n and J_p are electron and hole particle current densities, g is the generation rate, e is electronic charge (magnitude), E is electric field, ε is dielectric constant, N is background doping density, T is temperature, k is thermal conductivity and Q is the heat generated per unit volume.

The electron and hole continuity equations (1,2) and Poisson's equation (3) are discretised using the finite-difference approximation [7], while the heat conduction equation (4) is expressed in explicit form [12]. Maximum junction temperature is calculated following approaches given by A.R.Batchelor [13] and D.P.Kennedy [14], for integral heat sink and diamond heat sink diodes, respectively. The time-marching scheme, as used by P.A.Blakey et al. [8], has been applied. Frequency-domain results are obtained using a fast Fourier transform algorithm.

The oscillator circuit most frequently used in practice is the cross-coupled waveguide-coaxial configuration (Fig. 1). The corresponding first-order equivalent circuit model (Fig. 2) has been derived by K.Chang and R.L.Ebert [1].

OF-II

DESIGN PROCEDURE

The main aim of the IMPATT oscillator design is to produce the specified output power at a given frequency. The condition for circuit-controlled oscillations is given below [5]:

$$Y_D + Y_L = 0 \tag{5}$$

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where Y_D and Y_L are active device and passive circuit admittances, respectively. Let us suppose that the IMPATT diode is powerful enough to generate the desired power. In order to satisfy equation (5), it is neccessary to determine the device admittance and to match it by the passive circuit admittance Accordingly, the design method consists of two stages: firstly, the diode admittance is calculated at a single operating frequency; secondly, the dimensions of the oscillator circuit are modified so that condition (5) is fulfilled at the same frequency.

This approach allows a straightforward calculation of the dependence of the oscillator output power upon oscillating frequency. The basic idea is to match the IMPATT diode admittance to the modified passive circuit admittance. The circuit admittance is altered first (e.g. by varying the position of the movable waveguide short circuit) and then the following system of non-linear equations is solved:

$$G_D(f,V_{RF}) + G_L(f) = 0$$

$$B_D(f,V_{RF}) + B_L(f) = 0 \qquad (6)$$

$$Y_D = G_D + jB_D \, , \, Y_L = G_L + jB_L$$

where f is the frequency and V_{RF} is the amplitude of the RF voltage. The solution of (6) is obtained using the operating frequency as the starting point for the calculation of consecutive points for both higher and lower frequencies.

NUMERICAL RESULTS

The accuracy of the method is confirmed by comparison with experimental results presented by U.C.Ray et al. [2]. In this paper a simplified design approach for a W-band CW IMPATT oscillator is described, based on the same passive circuit model as presented here, but using a small-signal device admittance. Instead of taking into account the admittance of the actual diode built into oscillator, Ray et al. used the small-signal characteristics of a similar diode. Since neither large-signal nor small-signal impedances of the actual diode used are available, the direct comparison of our IMPATT diode simulation is impossible. Alternatively, we have calculated the large-signal diode impedance at 90.4 GHz, where the measured RF power versus frequency response of the oscillator peaks [2]. Diode parameters, together with diode impedance are summarized in Table I.

In order to check the proposed passive circuit design, three oscillator cavity dimensions are chosen to be variable. The adjustible parameters are: the sliding short position, the length of the lower coaxial port and the post diameter, the latter two characterising a coaxial resonator. The diode matching is performed as described in Section III. During the calculation the position of the waveguide short is held constant, while the other two parameters are calculated. Numerical results compare very well with the original results (Table II).

Finally, the output power against frequency response of the oscillator has been calculated (Fig. 3). The curve corresponding to the numerical model follows that depicting experimental results fairly well, but the theoretical output power is about 2 dB higher than the measured one. This stems from the fact that our model does not take into account various losses, such as passive circuit losses, diode contacts and package losses etc. A reasonable estimate of these losses is 1-2 dB, therefore the numerical results are in very good agreement with experimental ones.

NUMERICAL EFFICIENCY

Since the IMPATT diode simulation is based on one of the most efficient numerical algorithms for physical modelling, one program run takes less than 10 seconds of Amdahl 580 CPU time. This enables intensive optimisation of diode parameters.

The oscillator circuit model is even more efficient. Equation (5) is solved from an optimisation subroutine which seek to minimise $| Y_D + Y_L |^2$, by varying the passive circuit dimensions. One step in the minimisation procedure takes between 1 and 5 CPU seconds. Minimisation is accomplished in very few steps, usually less than five. The optimisation software used is from the NAG FORTRAN library.

The non-linear system of equations (6) is solved by the Newton-Rapson method. At the moment, simulation of one point of the output power-oscillating frequency curve takes 160 CPU seconds on average, but certain reductions may be achieved by method modification.

CONCLUSION

A computer-aided design method has been developed to synthesise millimetre-wave IMPATT oscillators. Theoretically derived oscillator characteristics are in good agreement with experimental data. These results look extremly encouraging. Improvements in accuracy require refinement of the passive circuit model and inclusion of losses. This method may be easily extended to model harmonic oscillators.

REFERENCES

[1] K.Chang and R.L.Ebert, "W-Band Power Combiner Design", IEEE Trans. on Microwave Theory Tech., vol.MTT-28, pp.295-305, Apr. 1980.

[2] U.C.Ray et al., "A Practical Approach to the Design of a W-Band IMPATT Oscillator", Microwave Journal, vol.32, pp.157-162, Nov. 1989.

[3] B.D.Bates, "A Comparison of IMPATT Oscillator Power and Frequency Above 100 GHz with Results Derived from Theoretical Models", IEEE Trans. on Microwave Theory Tech., vol.MTT-32, pp.1394-1398, Oct. 1984.

[4] T.Goeller and F.X.Kaertner, "Time-Domain Modelling of IMPATT Oscillators", IEEE Trans. on Circuits Systems, vol.36, pp.988-995, July 1989.

[5] K.Kurokawa, "Some Basic Characteristics of Broadband Negative Resistance Oscillator Circuits", Bell Syst. Tech. J., vol.48, pp.1937-1955, 1969.

[6] D.L.Scharfetter and H.K.Gummel, "Large-Signal Analysis of a Silicon Read Diode Oscillator", IEEE Trans. on Electron Devices, vol.ED-16, pp.64-77, Jan. 1969.

[7] P.A.Blakey et al., "Comprehensive Models for the Analysis of High-Efficiency GaAs IMPATTs", IEEE Trans. on Electron Devices, vol.ED-25, pp.674-682, June 1978.

[8] P.A.Blakey et al., "Large-Signal Time-Domain Modelling of Avalanche Diodes", IEEE Trans. on Electron Devices, vol.ED-26, pp.1718-1728, Nov. 1979.

[9] R.K.Mains et al., "Simulation of GaAs IMPATT Diodes Including Energy and Velocity Transport Equations", IEEE Trans. on Electron Devices, vol.ED-30, pp.1327-1338, Oct. 1983.

[10] C.Dalle and P.A.Rolland, "Drift-Diffusion Versus Energy Model for Millimetre-Wave IMPATT Diodes Modelling", Int. J. Num. Modelling, vol.2, pp.61-73, 1989.

[11] P.A.Blakey et al., "Millimetre-Wave IMPATT Diode Modelling", Proc. 8th Cornell Conf. on Microwave Semiconductor Devices and Circuits, pp.361-369, Aug. 1981.

[12] M.Becker, "Heat Transfer - A Modern Approach", pp.52-59, Plenum Press, New York, 1986.

[13] A.R.Batchelor, "Thermal Design Considerations for GaAs Transferred-Electron Devices", PhD Thesis, pp.50-53, the University of Leeds, 1990.

[14] D.P.Kennedy, "Spreading Resistance in Cylindrical Semiconductor Devices", J. of App. Physics, vol.31, pp.1490-1497, Aug. 1960.

TABLE I

Epitaxial layer	Doping level	Thickness (μm)
p^+	1.0E20	0.20
p	2.8E17	0.20
n	2.1E17	0.30
n^+	5.0E19	12.0
Junction area: 1.06E-5 cm^2 Junction temperature: 250°C DC current density: 24 kA/cm^2		
Diode impedance at 90.4 GHz (ohm) : (-1.55, -8.97)		

Data of Hughes W-band 100 mW CW IMPATT diode

TABLE II

	Post diameter (mm)	Length of coaxial port (mm)	Short-circuit position (mm)
Data from [2]	0.44	0.127	0.50-0.54
Theory	0.445	0.112	0.50

Comparison of theoretical and actual passive circuit dimensions

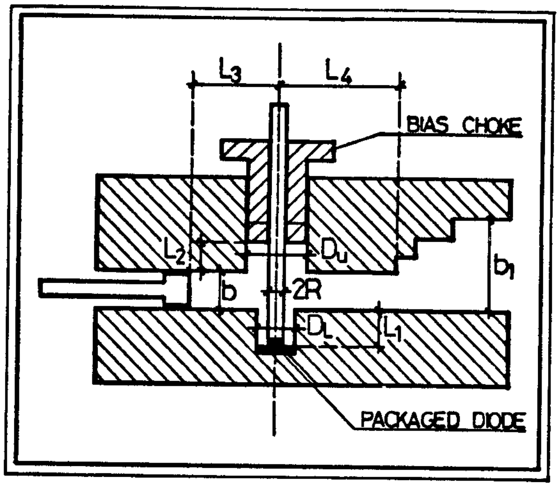

Fig. 1 A cross-coupled coaxial-waveguide mounting structure.

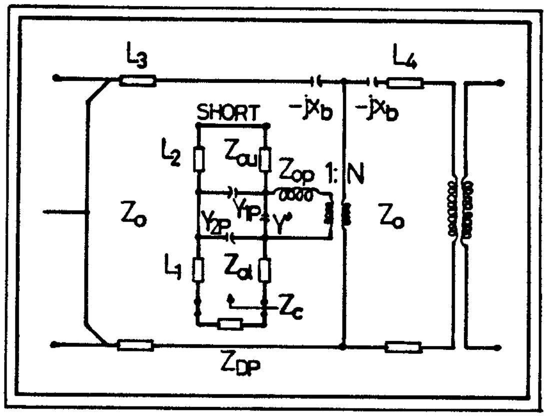

Fig. 2 Equivalent circuit of the structure depicted in Figure 1.

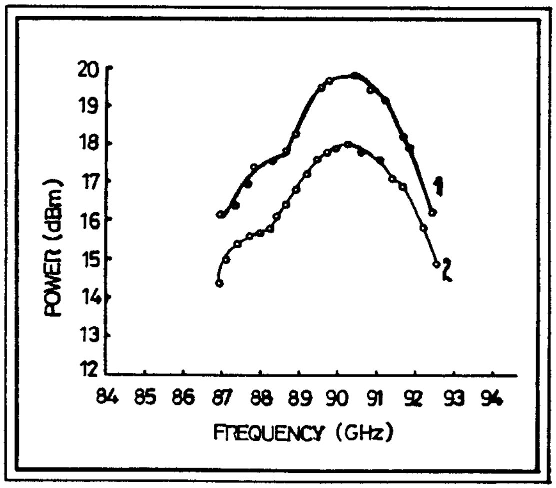

Fig. 3 Theoretical (1) and experimental (2) RF power versus frequency response of the oscillator.