DEVICE-CIRCUIT INTERACTION SIMULATION OF A TRAPATT AMPLIFIER*

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ABSTRACT

Computer programs have been developed which perform a device-circuit interaction simulation of a TRAPATT amplifier for which experimental results were previously reported. The coaxial line with tuning slugs and the TRAPATT diode are simulated in the time domain. All of the device and circuit parameters reported experimentally are incorporated in the computer simulation. Theoretical results are presented and compared with experimental data.

Introduction

A circuit simulation program has been combined with an appropriate device model to analyze the performance of a reflection TRAPATT amplifier. The circuit response is evaluated by launching an RF voltage wave (corresponding to the input signal which is to be amplified) at one end of a coaxial cavity circuit structure which is terminated at the other end by the TRAPATT diode. The combined circuit device simulation permits the instantaneous diode terminal voltage and current density to be obtained as a function of time. The bias circuit is also simulated along with the circulator which isolates the diode from the input and output networks. The results obtained from the computer simulation are compared with data obtained from an experimental amplifier.

Circuit Program

As part of an earlier study of TRAPATT oscillators, a computer program was developed[1] which accurately models a coaxial circuit consisting of an arbitrary tuning-slug configuration, a lumped-element package-mounting network, a dc blocking capacitor, a load resistor, and a bias source with arbitrary pulse rise time and amplitude. This program has been modified to simulate a TRAPATT amplifier circuit, by introducing a circulator-coupled input signal, inserting a lumped-element model for the circulator between the bias T and load resistor, and expanding the lumped element models for the package and bias T.

The program solves the circuit in the time domain by keeping track of the forward- and reverse-traveling waves and by computing the reflections at all the circuit discontinuities. Since the coaxial line is assumed lossless, a considerable savings in computer time is possible by storing the amplitudes of the incident and reflecting waves only at the discontinuities and noting the transit times between discontinuities. In calculating wave reflections, fringing capacitance is also included at the impedance discontinuities. To insure sufficient accuracy the 3.75 cm coaxial line is divided into 600 space steps.

The package, bias T, and circulator lumped element networks are solved by writing the state-variable equation[2] for each network. These equations are transformed into finite-difference equations by applying the trapezoidal rule.[3] From these equations, given the voltage wave incident on the network and the values of the state variables at a particular time, the amplitude of the reflected wave from the network is obtained.

The model chosen to represent the circulator is a lumped-element bandpass filter whose center frequency and bandwidth correspond to the specifications of the actual circulator used. The bias circuit model consists of a dc blocking capacitor, an RF blocking inductor, a current generator with a ramp turn-on characteristic, and a generator resistance.

Device Program

The device is assumed to have a 0.85 micron depletion layer width and a uniform doping concentration of 10^{16} acceptors/cm^3. This region is divided into 25 space steps at which the electric field, electron and hole concentrations, and particle currents are stored. The equations solved in the device simulation[4] are the continuity equation, Poisson's equation, and the current expressions obtained from the first-order solution of the Boltzmann transport equation. These equations are transformed into finite difference relations and are solved in both space and time, the space step being the distance between successive storage points within the depletion layer, and the time step being chosen from stability considerations. For a given diode terminal voltage, the current calculated by this simulation yields the particle current but not the displacement current. Therefore it is necessary to add the diode capacitance in shunt with the device to obtain the correct total current. This program was also written with the objective of minimizing the computation time, since for a typical simulation of 2 ns the device program is implemented on the order of 10^4 times.

Device-Circuit Interaction

Although these programs are relatively inexpensive to run, despite their complexity, it would still be prohibitively expensive to use them as design tools; i.e., to run the simulation for a wide range of circuit configurations until the desired gain and bandwidth are realized. The approach used in this study was to incorporate a circuit configuration for which amplifier characteristics had already been obtained experimentally.[5] The tuning slug positions and the component values for the lumped-element models of the package-mounting network and the bias-T were also measured and reported along with the diode depletion-layer width and doping concentrations.

The device-circuit configuration is shown in Fig. 1 while the complete amplifier configuration is illustrated in Fig. 2. The lumped elements to the left of point B in Fig. 1 constitute the package-mounting equivalent circuit. The current source I_{bias} generates the variable-rise-time bias pulse. C_B is the dc blocking capacitor while L_B represents the RF blocking inductor of the bias T. R_g is the bias generator resistance which may be varied to minimize low-frequency bias-circuit oscillations. An input signal voltage

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wave of the form $V_A = V_o \sin(\omega t)$ is launched from point A toward the circuit as indicated by the arrow.

The major circuit component for which no measurements or equivalent circuits were provided in reference [5] is the circulator. Specifications for the in-band characteristics of the circulator were obtained from the manufacturer. It was then assumed that a lumped-element bandpass filter of similar in-band characteristics was an adequate model for the circulator.

At the start of the simulation, it is assumed that the diode and circuit in Fig. 1 are in a dc state such that the diode is reverse biased at 3 V. At t = 0, the bias source is ramped on and the ac input wave is launched from point A toward the diode. Figure 3 shows typical device voltage and induced current-density waveforms during the initial transient period. The induced current is the total diode terminal current minus the displacement component and can be obtained from the expression

$$I_{induced} = \frac{1}{W}\int_0^W I(x)\,dx \quad , \qquad (1)$$

where W is the diode width and I(x) is the total particle current density at point x inside the diode. The coaxial-line transit time is 0.15 ns, as is apparent from Fig. 3. The pulse rise time for I_{bias} in this simulation is 1 ns; during the time interval from 0.15 to 1.15 ns the diode terminal voltage is seen to be the superposition of the linearly rising bias pulse and the incoming ac signal to be amplified. For this simulation the frequency of the V_A input wave was 8.73 GHz. The experimental amplifier had a midband gain of 5 dB at this frequency.[5] After approximately 5.5 ns of simulation, the diode voltage and induced current waveforms of Fig. 4 were obtained. Fourier analysis of these waveforms as well as the voltage at the load resistor R_L in Fig. 1 yields a gain of about 5 dB at the 8.73 GHz input frequency. The efficiency calculated from the waveforms was 15 percent which compares favorably with 18.5 percent reported experimentally.[5]

These simulations are currently being used to evaluate the TRAPATT device waveforms as well as the external circuit impedance as a function of frequency throughout the amplifier bandwidth. Such information can be used to design broadband TRAPATT amplifier circuits.

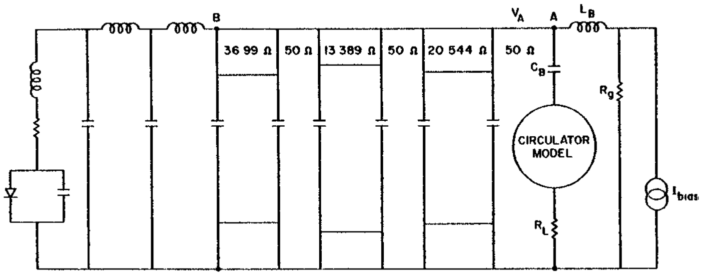

FIG. 1 Hughes Device-Circuit Interaction Model.

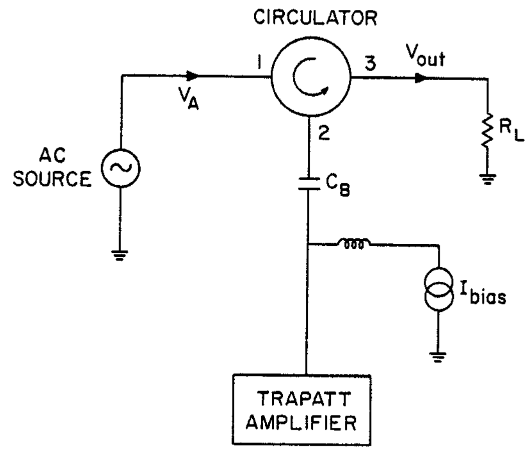

FIG. 2 Diode Bias and Circulator Coupled Input-Output Arrangement.

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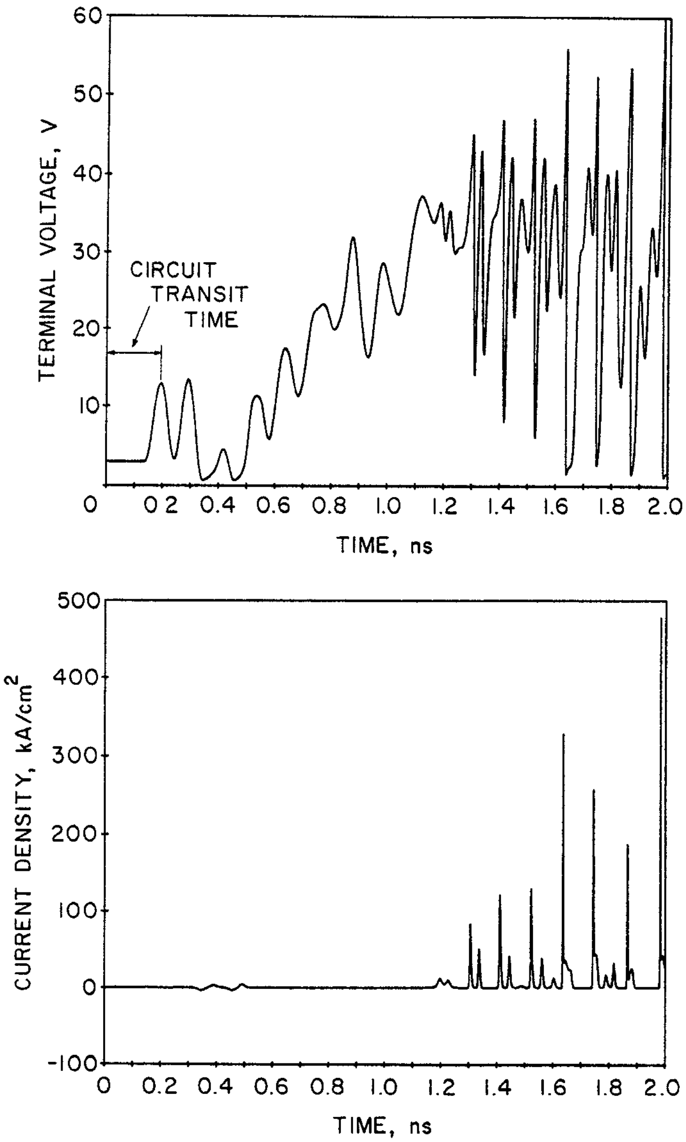

FIG. 3 Device Waveforms for the First 2 ns of Simulation. (0.85 µm Diode and Frequency = 8.7 GHz)

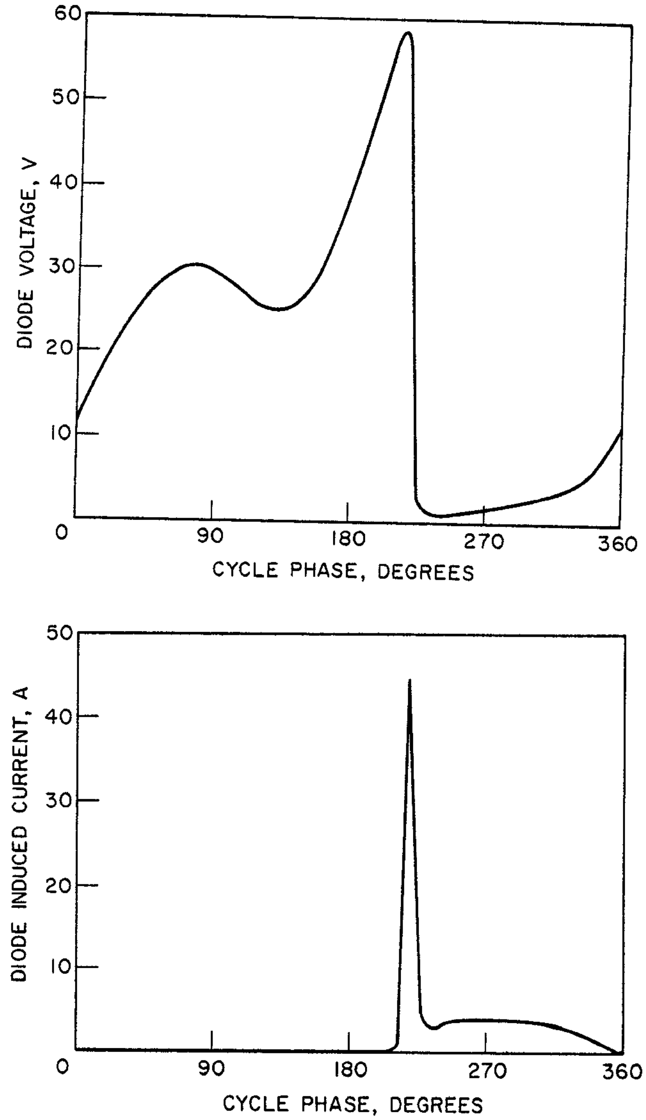

FIG. 4 Diode Waveforms at Midband.