Modeling of Nonlinear Dispersive Active Elements in TLM

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Abstract

The transmission line matrix (TLM) method is used for modeling of distributed active nonlinear domains embedded in planar microwave circuits. In this approach the nonlinearities are described by lumped elements connected to the nodes of a resistive TLM-network. With this approach the transient as well as the steady-state behaviour of nonlinear distributed active elements can be evaluated. In the paper we discuss the model of a distributed semiconductor diode. The distributed barrier is modelled by a resistive region. The physical cut-off characteristics of the semiconducting region is considered by lumped capacitors included into the TLM network. For an oscillator with a distributed diode the time history and the field contribution at different instants of time are given.

Introduction

The transmission line matrix (TLM) method is used for modeling of distributed active nonlinear domains embedded in planar microwave circuits. Time domain modeling of active circuits is advantageous for the evaluation of the transient behaviour and for the evaluation of spatial distributed active circuits. In this approach nonlinearities are modeled by connecting lumped elements to the nodes of a TLM-network via a transmission line of $\Delta l/2$ length [1][2]. The value of the of the stub admittance Y_s may be choosen arbitrarily. Appropriate values of Y_r may simplify the calculation and the system of nonlinear equations describing the nonlinear circuit element can be solved without recursion for each step of the TLM algorithm. In general the dependence between the node voltage $v(t)$ and the current $i(t)$ flowing into the nonlinear admittance will be governed by a nonlinear system of first order ordinary differential equations.

In the two-dimensional TLM network consisting of parallel connections of transmission lines the electromagnetic field is described by voltage wave amplitudes. We introduce the voltage wave amplitudes $V_5^r(t)$ describing a wave travelling from the TLM node toward the nonlinear admittance, and $V_5^i(t)$ describing a voltage wave incident from the nonlinear admittance onto the TLM node. The amplitude of the reflected pulses at the node is calculated by multiplication of the incident pulse vector with the node scattering matrix S:

$$ {}_kV^{r\,T} = \mathbf{S}\ {}_kV^{i\,T} \qquad (1)$$

Modeling of an active region in a resistive mesh

In the following we discuss the model of a distributed semiconductor diode. The equations describing the distributed barrier are given by the two-dimensional lossy line equations

$$\frac{\partial v}{\partial x} = -Ri_x - L_d\frac{\partial i_x}{\partial t} \qquad (2)$$

$$\frac{\partial v}{\partial y} = -Ri_y - L_d\frac{\partial i_y}{\partial t} \qquad (3)$$

$$\frac{\partial i_x}{\partial x} + \frac{\partial i_y}{\partial y} = -Gv - C\frac{\partial v}{\partial t} - f(v) \qquad (4)$$

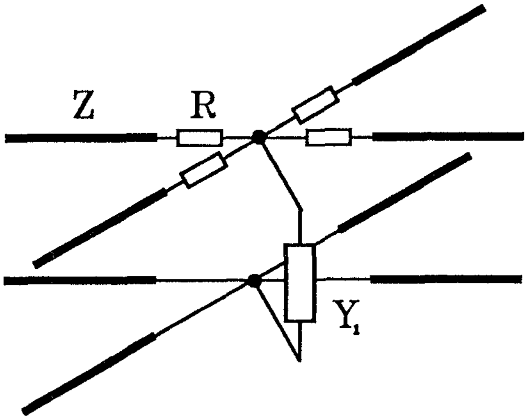

Figure 1: Schematic of a general nonlinear resistive TLM node

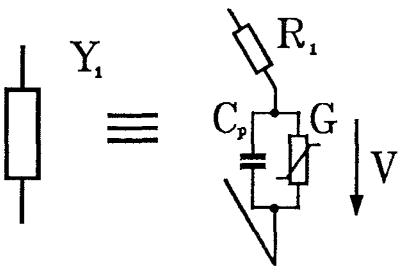

Figure 2: Example for lumped nonlinear circuit

The nonlinear barrier series resistance and the nonlinear barrier capacitance are modeled by lumped nonlinear resistors and capacitors connected via lossy lines in parallel to the nodes. The resistive stub lines as well as the resistive mesh lines model the lossy semiconductor regions adjacent to the barrier. The general case of a nonlinear TLM node is shown in Fig. 1. The nodes of the TLM mesh are connected by transmission lines in series to resistors. The use of a resistive TLM-mesh for the solution of a diffusion equation has been shown by Johns [4][5]. The terms containing L_d and C in eqs. (2) to (4) correspond to the two-dimensional lossless line and are modeled as usual by the TLM mesh. The appropriate value for the stub impedance $Z_s = 1/Y_s$ is dependent on the stub resistance R_s and the network parameters R and Z. With this choice the voltage wave V_s^r reflected to the nonlinear circuit is independent of the incident pulse at the stub, and therefore the linear and nonlinear part of the TLM node are decoupled. With the total admittance Y of all adjacent branches at the TLM node the two-dimensional lossy line equations may be written in an explicit difference scheme [5]

$$ {}_{k+1}\phi = \left[\frac{2}{R+Z}\sum_{l=1}^{4} {}_kV_l^i + \frac{2}{R_s+Z_s}\,{}_kV_5^i\right]\frac{1}{Y} \tag{5} $$

$$ {}_{k+1}V_m^r = \frac{Z}{R+Z}\,{}_{k+1}\phi + \frac{R-Z}{R+Z}\,{}_kV_m^i \tag{6} $$

$$ {}_{k+1}V_5^r = \frac{Z_s}{R_s+Z_s}\,{}_{k+1}\phi + \frac{R_s-Z_s}{R_s+Z_s}\,{}_kV_5^i \tag{7} $$

where V_m^r and V_m^i is the reflected and incident pulse at the mth terminal of the TLM-node, and V_s^r and V_s^i is the reflected and incident pulse at the stub linked to the lumped element circuit. The resistance at the branch 5 can be also considered in the lumped series resistor R_1 interior the nonlinear lumped element circuit, so that eq. (7) may be simplified to

$$ {}_{k+1}V_5^r = {}_{k+1}\phi - {}_kV_5^i \tag{8} $$

The lumped element circuit can be described by state equations in the general form

$$ {}_{k+1}\phi = f_1({}_k\phi) + f_2({}_k\mathbf{V}^r) \tag{9} $$

$$ {}_{k+1}\mathbf{V}^i = f_3({}_{k+1}\phi) + f_4({}_k\mathbf{V}^r) \tag{10} $$

with the state vector ϕ, the input vector $\mathbf{V}^r$ and the output vector $\mathbf{V}^r$. If the state equations are written in this explicit form, the values of the state vector at the timestep k can be calculated from the values of the state vector at the previous time steps. The nonlinear dependence between current and voltage is described by a polynomial function $G({}_kV)$.

In the case of the simple configuration of Fig. 2 we can establish the following state equations

$$ {}_{k+1}V = {}_kV + \Delta t\frac{1}{C}\left[\frac{NY_s}{1+NR_1Y_s}\,{}_kV - - G({}_kV) + \frac{1+\Gamma}{R}\,{}_kV^r\right] \tag{11} $$

$$ {}_{k+1}V^i = \frac{1}{1+NR_1Y_s}\,{}_{k+1}V + \Gamma\,{}_kV^r \tag{12} $$

where the state variable V is the inner voltage, which controls the current of the nonlinear conductance. The output variable is the incident pulse at branch 5 of the TLM node at time step $k+1$, while the input variable is the pulse reflected into branch 5. The abbreviation Γ is given by eq. (13)

$$\Gamma = \frac{NR_1Y_s - 1}{NR_1Y_s + 1} \tag{13}$$

where N is the number of TLM nodes connected to the diode region.

A DISTRIBUTED OSCILLATOR

As an example a spatial distributed oscillator was investigated by the presented approach. A diode, which has the size of 6x6 Δl^2, was inserted into a cylindrical resonator. The oscillation increases from an initial signal injected at the input area to start the process as shown in Fig. 3. The initial signal may be interpreted as thermal noise in the lossy semiconductor region. A three-dimensional view of the field contribution at the steady state of the diode region is given by Fig. 4. A small difference in phase occur between the signals inside the diode and inside the resonator, respectively. Also time delays inside the diode region can be observed. The time history of the oscillation is shown in Fig. 5. The initial noise signal decreases while the oscillation increases.

Due to the stopband/passband characteristics of the lattice structure also spurios modes are excited in active regions of the TLM network. These modes will be suppressed by a capacitor connected in parallel to the nonlinear admittance to avoid distortion of the output signal or numerical overflows. An alternative approach is the implementation of a numerical lowpass filter to attenuate the frequency spectrum near the network cut-off frequency.

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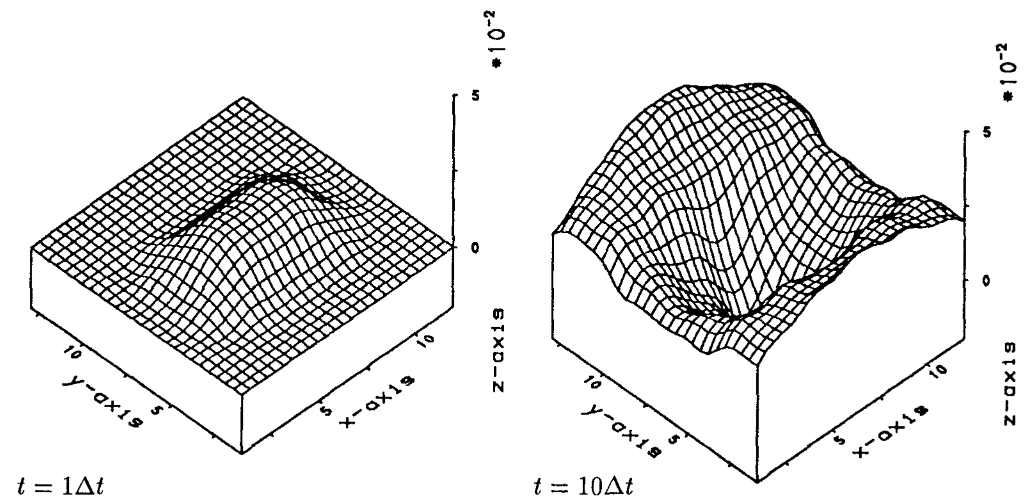

Figure 3: Initial perturbation of the diode region.

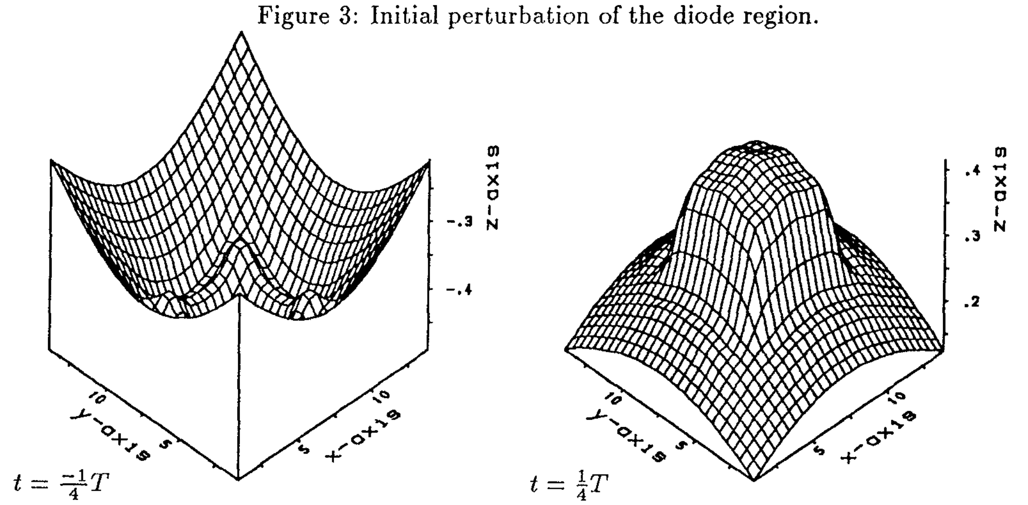

Figure 4: Field simulation the diode region.

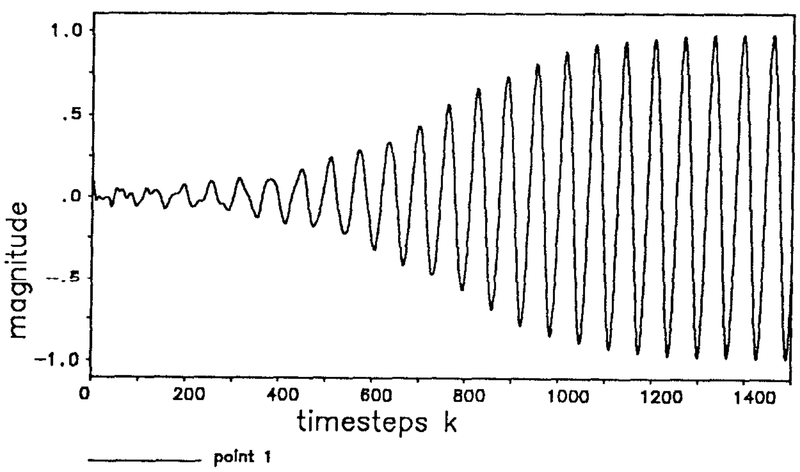

Figure 5: Time dependence of the oscillator output signal.