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A General Planar Circuit Simulator Based on Two-Dimensional TLM Method

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Abstract

A two-dimensional circuit simulator based on the TLM method (2D-TLM) has been developed. It can analyze two-dimensional circuits of arbitrary geometry containing both linear and nonlinear media. The circuit geometry is input graphically. Both time-domain and frequency-domain responses can be computed and visualized. As examples, a microstrip lowpass filter, a microstrip varactor multiplier, and a waveguide post-coupled filter have be analyzed and compared with other methods.

Introduction

The two-dimensional Transmission-Line Matrix method (2D-TLM) has been invented and pioneered by Johns and Beurle [1]. An extensive list of references on this subject can be founded in a review paper by Hoefer [2]. The 2D-TLM algorithm is indeed a very powerful time-domian method for planar circuit simulation, especially when the circuit geometry is too complicated for traditional analysis. The earlier applications of the 2D-TLM method concentrated on finding the eigen-frequencies and propagation constants of structures; however, by simulating broadband absorbing walls the S-paramters of the two-dimensional circuits can be found directly from their impulse response. Indeed, the transfer function of the two-port structure terminated with absorbing walls is S_{21}. Once S_{21} is known, S_{11} can be found easily if the structure is lossless.

In some applications the input and output waveforms may be of interest and hence the traditional frequency domain analysis cannot be used directly. Furthermore, it is well known that frequency domain methods cannot be used directly to perform non-linear circuit analysis. Time-domain methods do not have this limitation and among the time-domain methods, TLM method has the great advantage that it is inherently stable, i.e. it always converges. The 2D-TLM method can also be used to simulate non-linear elements such as varactor diodes by iteratively updating the permittivity stubs in a selected area of the TLM-network [3].

The traditional TLM programs are difficult to use. The user must first draw a discretized sketch of the structure and then transform the drawing into a very complicated input file. This is a time-consumming and error prone process. The 2D-TLM planar circuit simulator described in this paper has a user-friendly graphic interface. This allows very complicated circuit geometry to be input in a relatively short period of time. Some characteristics of this planar circuit simulator are:

(1) User-friendly graphic interfaces,
(2) Arbitrary input/output points,
(3) Non-linear simulation — varactor diode,
(4) Broadband absorbing walls,
(5) Discrete and fast Fourier transform capabilities,
(6) Matched calibrated voltage source of arbitrary waveform.

Modelling of Microstrip Circuits

Simulation of microstrip circuits in the frequency domain is usually done through the use of empirical expressions. These expressions are quite accurate in the designated frequency range, and many of them are used in commercial CAD software to implement circuit elements of simple geometry. However in some design situations it may be advantageous to use elements of complicated geometry. The TLM method is a good alternative for solving this type of problem. This method allows circuit elements of arbitrary geometry to be simulated, provided that a planar equivalent of the structure can be specified; this approach has been used extensively by Wolff [4]. The accuracy of the result is limited only by the discretization size of the TLM mesh.

The microstrip is modelled as a parallel plate waveguide supporting fields independent of the y-direction. The effective width w_{eff} of that model is

$$w_{eff} = \frac{h}{Z_{o\mu}}\sqrt{\frac{\mu_o}{\epsilon_o \epsilon_{re}}}$$

where, [5]:

$$\epsilon_{re} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left(1 + \frac{12}{w/h}\right)^{-1/2}$$

$$Z_{o\mu} = \frac{120\pi/\sqrt{\epsilon_{re}}}{w/h + 1.393 + 0.667 ln(w/h + 1.444)}$$

and

c : speed of light in vaccum,
w: actural width of the microstrip line,
h : substrate thickness.

To simulate the microstrip by using 2D-TLM, the admittance of the loading stubs in each simulation region is:

$$y_o = 4(\epsilon_{re} - 1)$$

Since ϵ_{re} is assumed to be independent of frequency in the planar TEM approach, it is not difficult to implement a wideband absorbing wall of local reflection coefficient Γ_{line} such that the global reflection coefficient Γ_{mesh} is zero at the termination end. If the 2D-TLM mesh is terminated by such a wall then the transfer function at port-2 of the network in Figure-1 is $S_{21}(\omega)$. This is because if

$$a_1(\omega) = 1 \quad \text{because of impulse excitation}$$
$$a_2(\omega) = 0 \quad \text{because of } \Gamma_{mesh} = 0$$

then

$$S_{21}(\omega) = b_2(\omega) = H_{21}(\omega)$$

where $H_{21}(\omega)$ is the transfer functions of the network at port-2 when the input impulse is applied to port-1. The reflection coefficient Γ_{line} terminating the mesh lines when modeling a non-dispersive load of impedance Z_l is:

$$\Gamma_{line} = \frac{1 - \sqrt{2\epsilon_{re}}}{1 + \sqrt{2\epsilon_{re}}}$$

A microstrip lowpass filter was simulated by using the 2D-TLM method and the input and output end were terminated by such absorbing walls. The equivalent 2D-TLM model of this lowpass filter is shown in Figure-2. A row of impulses were used to excite the TLM network at the input end, and the output was taken at the other end. The impulse response and its Fourier transform are shown in Figure-3. The response of this filter was also found with Touchstone™ (system impedance $= Z_{o\mu} = 20.453\Omega$), and the insertion loss obtained is shown in Figure-4. As expected the results from these two methods are indeed in good agreement with each other.

Modelling of Non-linear Elements
Varactor Diode

The capacitance of a varactor diode is a function of the total voltage across the diode terminals. The variation of this capacitance can be modelled quite effectively by the use of the 2D-TLM method. Because the diode area is small compared to the operating wavelength, one can assume that the voltage is constant over the "diode area". Therefore the loading stubs in the "diode area" have the same admittance value and vary as a function of the total voltage at a point in the "diode area". The admittance value (for an abrupt diode) in the "diode area" is [3]:

$$y_o = 4\left[\frac{C_{jv} + C_{dv} + C_p}{C_a} - 1\right]$$

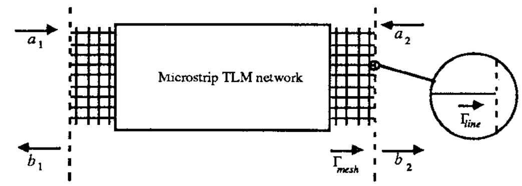

Figure 1: A TLM network diagram. If the local reflection coefficient in each mesh line (Γ_{line}) is $\frac{1-\sqrt{2\epsilon_{re}}}{1+\sqrt{2\epsilon_{re}}}$ then there would be no global reflection in the 2D-TLM mesh, i.e. $\Gamma_{mesh} = 0$.

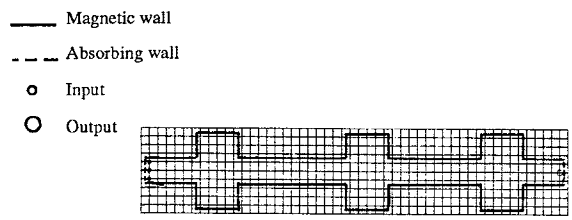

Figure 2: The equivalent 2D-TLM model (loading stubs are not shown) of a microstrip lowpass filter (ϵ_r=2.2, w/h=10, Δl=1mm and Γ_{line}=-0.3338).

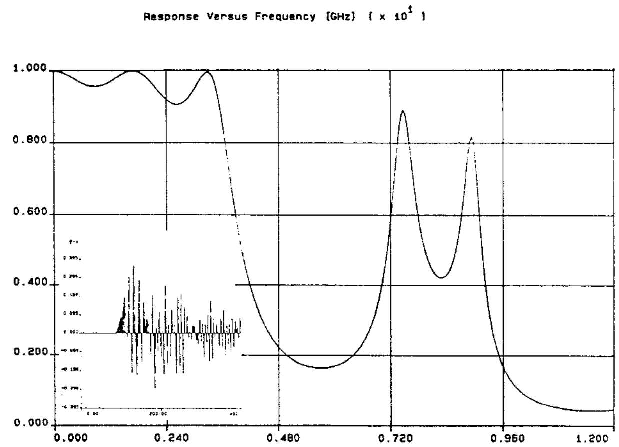

Figure 3: The impulse response and its Fourier transform of the lowpass filter depicted in Figure-2.

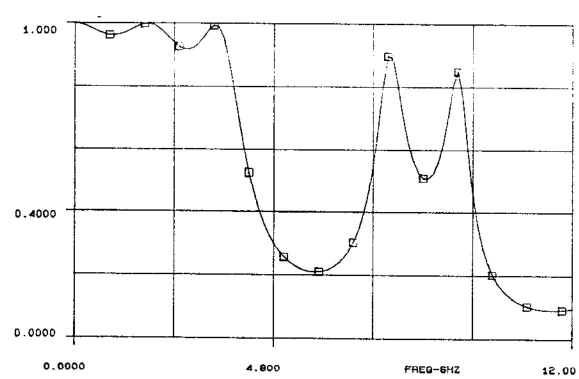

Figure 4: The S_{21} characteristic of the lowpass filter depicted in Figure-2, obtained with Touchstone™

where

C_{jv} = voltage dependent junction capacitance
$= \frac{C_{jb}}{\sqrt{1-\frac{v(t)}{\phi_o - V_{bias}}}}$
$C_{jb} = \frac{C_{jo}}{\sqrt{1-\frac{V_{bias}}{\phi_o}}}$
C_{jo} = zero bias capacitance
C_{dv} = voltage dependent diffusion capacitance
$= 3.212 \times 10^{-18} exp(40 \times (v(t) + V_{bias})$
C_p = packaging capacitance
C_a = capacitance due to diode area
ϕ_o = built-in potential

To simulate the varactor response in the time-domain a matched source must be implemented. Figure-5 depicts the voltage impulses at time k and k+1. The reflected impulse at time k+1 due to the incident impulse at time k are:

$$V^r_{k+1} = \Gamma_{line} \times V^i_k$$

and the impulses due to the source arriving at the same location at time k+1 have the value:

$$V^{source}_{k+1} = \frac{Z_o}{Z_s + Z_o} \times V^s_{k+1}$$

Because

$$\Gamma_{line} = \frac{1-\sqrt{2\epsilon_{re}}}{1+\sqrt{2\epsilon_{re}}} = \frac{1-Z_o/Z_s}{1+Z_o/Z_s}$$

Therefore

$$V^{r\text{-}total}_{k+1} = \frac{\sqrt{2\epsilon_{re}}}{1+\sqrt{2\epsilon_{re}}} \times V^s_{k+1} + \frac{1-\sqrt{2\epsilon_{re}}}{1+\sqrt{2\epsilon_{re}}} \times V^i_k$$

Figure-6 depicts the input waveform and the equivalent TLM mesh for a varactor diode (MA46601G) in a microstrip environment. Some important parameters used in the simulation are:

$$\epsilon_{re} = 1.95416$$
$$\Delta l = 0.103\text{mm}$$
$$\phi_o = 1.3\text{volts}$$
$$C_{jo} = 0.908 \times 10^{-12}\text{F}$$
$$C_p = 0.130 \times 10^{-12}\text{F}$$
$$C_a = \frac{\epsilon_o \epsilon_{re} nm(\Delta l)^2}{h} = 0.505869 \times 10^{-14}\text{F}$$

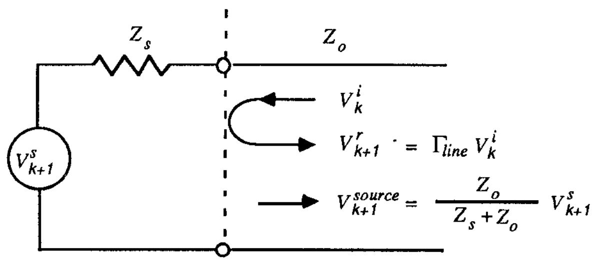

Figure 5: The resultant impulses at time k+1 due to the incident impulse at time k and the out-going impulse from a matched source at time k+1.

Figure-7 depicts the non-linear and the frequency multiplication effects at V_{bisa}=0.2 volts. This result shows that the TLM-model used in the simulation is indeed a valid one. In fact, this 2D-TLM method was used to design frequency multipliers and dividers [3] and the experimental results were in good agreement with the simulation results.

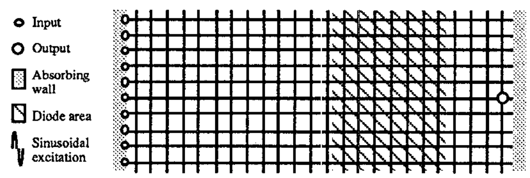

Figure 6: A TLM model for a varactor diode (loading stubs are not shown). The excitation waveform on the left is applied to all input nodes.

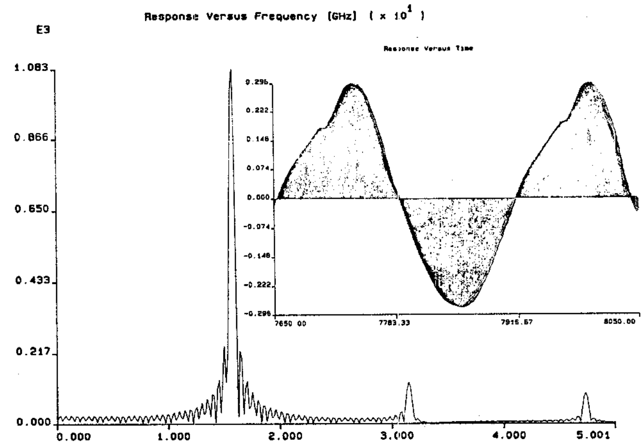

Figure 7: The output waveform and their transfer functions at V_{bias} = 0.2 volts.

Modelling of Rectangular Waveguide Compoments

The 2D-TLM has previously been applied to waveguide analysis by Johns and Beurle [1]. In order to simulate the transmission characteristics of waveguide components absorbing walls must be placed at both the input and the output ends of the component. Even though waveguide is dispersive it is not difficult to implement a narrowband absorbing wall at the operating frequency band. The relative effective dielectric constant ϵ_{re} of a rectangular waveguide is:

$$\epsilon_{re}(f) = \epsilon_r - \left(\frac{c_o}{2af}\right)^2 = \epsilon_r - \frac{1}{8}\left(\frac{k}{N}\right)^2 = \epsilon_{re}(k)$$

where

ϵ_r : relative dielectric constant of the dielectric filling the waveguide
c_o : speed of light in air
a : waveguide width = $N\Delta l$
f : operating frequency = $\frac{\sqrt{2}C_o}{k\Delta l}$
k : number of impulses in a period
N : total number of nodes across the waveguide

In order to have total transmission at f_o, the mesh lines must be terminated in a reflection coefficient:

$$\Gamma_{f_o} = \frac{1-\sqrt{2\epsilon_{re}(f_o)}}{1+\sqrt{2\epsilon_{re}(f_o)}} = \frac{1-\sqrt{2\epsilon_{re}(k_o)}}{1+\sqrt{2\epsilon_{re}(k_o)}} = \Gamma_{k_o}$$

For the TE_{10} mode, the electric field has a half-sine wave profile across the waveguide; hence the relative magnitude of the impulses across the waveguide is:

$$A(n) = sin\left(\frac{\pi}{N}(n-0.5)\right)$$

where n is the node-number, $1 \leq n \leq N$.

Figure-8 depicts a TLM mesh and the impulse response of a WR28 waveguide (N=11, k=20, Δl=0.64655mm and hence f_o=32.8GHz). Strictly speaking Γ_{f_o} is only correct at $f=f_o$=32.8GHz, but Figure-8 shows that within the operating freqency band (26 to 40 GHz) the transfer function is very flat — i.e. the error due to Γ_{f_o} does not affect the transmission characteristics drastically. Figure-9 depicts a TLM mesh and a WR28 waveguide post-coupled bandpass filter. A mode-matching program was also used to analyze this filter, and the result is in good agreement with the 2D-TLM simulation.

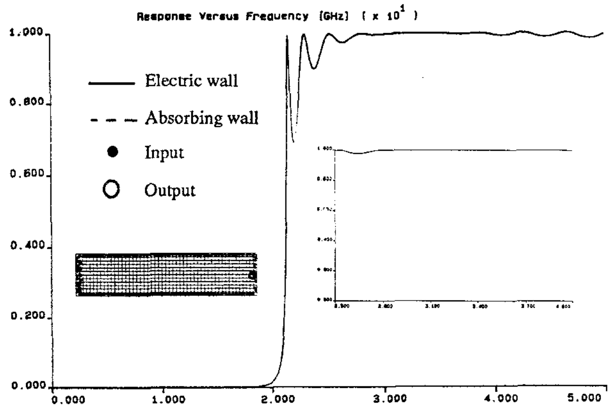

Figure 8: A TLM model for WR28 (TE_{10} mode). The transfer function (or S_{21}) is very flat in the operating band which indicates the absorbing boundary is indeed very good in this frequency range.

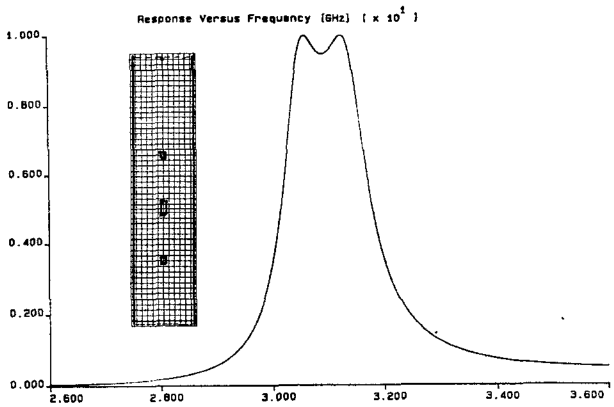

Figure 9: A TLM model and S_{21} for a waveguide post coupled bandpass filter.

Conclusion

A very user-friendly planar circuit simulator has been implemented by using the 2D-TLM method. This simulator allows the user to simulate non-dispersive microstrip circuits, non-linear elements (such as varactor diode) and waveguide circuits as long as the fields are independent of the y-direction (TE_{mo}).

Matched sources and absorbing walls are implemented in this 2D-TLM circuit simulator. The implementation of these circuit elements allows the S-parameters of the (linear) structure to be computed directly from a single impulse response rather than via the traditional "voltage-standing-wave-method"; hence both the computation time and memory requirements are reduced. Since microstrip is not very dispersive at low frequency the matched source and absorbing wall are valid in a very wide frequency band. Even though waveguide is dispersive, the simulation result shows that the narraw-band absorbing wall is indeed very good over the operating frequency band. A varactor diode model has also been implemented in this planar circuit simulator. The simulation result shows clearly that the non-linear and frequency multiplication effects; experiments [3] has confirmed that the diode model used in this TLM simulator is indeed a good approximation of the real device.

The simulation results show that this 2D-TLM simulatior is a very powerful time-domain simulation tool for complicated circuits. To simulate circuits that have coupling and more complicated geometry the 3D-TLM method must be used. In addition wideband absorbing boundary must be implemented for waveguide in order for the impulse response to be valid in a larger frequency band. This extension is presently under study.

Reference

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