Circuit Level Modelling of Spatially Distributed mm and sub mm-Wave Systems

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Abstract—Modelling of millimeter-wave and submillimeter-wave systems have generally been developed from a circuit perspective with the effect of the electromagnetic environment modeled essentially as lumped elements. Recent developments in steady-state and transient analyses integrating circuit and electromagnetic modeling are presented.

I. INTRODUCTION

In millimeter-wave and submillimeter-wave circuits the electromagnetic environment has a crucial effect on system performance. Generally design proceeds with a very large amount of intuition and limited modeling. The pioneering work of Eisenhart and Khan [1] exemplifies an approach to modeling the effect of waveguide-based structures. In this work described it was shown for the first time that quite sophisticated and accurate models could be developed for a three-dimensional waveguide system. This model has been used extensively in the design of post mounted waveguide components. The model developed is compatible with simple nonlinear circuit simulation. Millimeter-wave and submillimeter wave circuits are becoming ever more commercially viable and along with the large scale production design practices must evolve to be more sophisticated

Millimeter-wave and submillimeter wave circuits are generally simple consisting of single-ended active circuits driving a one-port "electromagnetic" environment. Recently a new family of millimeter-wave circuits has been proposed and are being explored. These are the active spatial or quasi-optical power combining structures. Most spatial power combining systems can be illustrated by the configurations in Figure 1 [2], [3], [4], [5], [6]. Here a waveguide horn spreads the energy from an input waveguide over a surface that could be several wavelengths on a side. This spatially distributed signal impacts an array of amplifiers perhaps arranged in a grid, or an array of coupled slots, etc. The reverse function is implemented on the obverse side where the output from the individual amplifiers is combined to produce a single coherent output beam.

Recent advances in the new technology of two-dimensional quasi-optical power combining promise significant progress in bringing the advantages of solid state monolithic technology to moderate and high power millimeter-wave applications. A major characteristic of the conventional quasi-optical circuits is the use of three-dimensional free space for the power combining. In [8], [9] and [10] this concept is extended leading to the development of a quasi-optical system which combines power in two dimensions such as shown in Figure 2. The 2D geometry can lead to circuits which are less sensitive to instabilities and are easier to optimize for efficiency as well as being smaller and lighter.

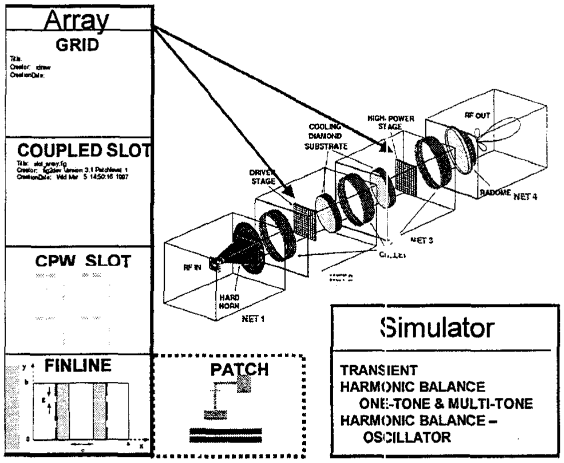

Figure 1. A three dimensional transmission-mode spatially distributed amplifying system.

Spatial power combining systems are complex the electromagnetic environment is crucial to the operation of the system. In this paper necessary strategies for analyzing such structures are discussed. Modeling and simulation are important for their own right. Just as importantly characterization serves the purpose of increasing the understanding of the intrinsic behaviour of these systems and can serve to isolate effects that can then be addressed one by one to achieve desired performance.

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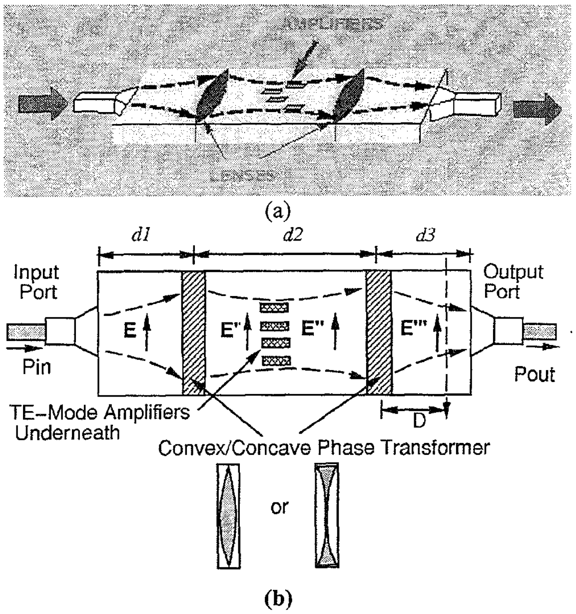


(a)

(b)

Figure 2. A two dimensional travelling wave mode spatially distributed amplifying system.

II. DEVELOPMENT

The major obstacle to integrating electromagnetic analysis with circuit analysis and hence conventional simulation is that circuits represent a very high level of abstraction. The reverent appreciation of this quickly evolves when trying to merge disparate forms of modeling. A circuit is essentially a simple graphical construct for coupling together algebraic and first order differential equations. These various equations arise from the constitutive relations of the individual elements and Kirchoff's current law specifies what form these individual equations must be in, and how the equations are coupled. Circuits do get a bit more sophisticated than this but this is the essential abstraction. The analysis thus described is called nodal admittance analysis. It is important to note that circuits have no sense of space – a circuit is defined as though it existed at point. How then is an electromagnetic structure which inherently is distributed in space to be inserted in to this system? Two approaches are being pursued. One of these is to insert the device equations into an appropriate electromagnetic simulator such as a finite difference time domain (FDTD) simulator [12], [13]. This approach reduces the level of abstraction of the "circuit" and embeds the constitutive relations of the conventional circuit elements in the analysis grid of the FDTD method. An alternative is to retain the high-level circuit abstraction and incorporate the results of a field analysis (the spatially distributed circuit) into a circuit structure [11], [14], [15], [16], see Figure 3. Thus the problem is one of taking an electromagnetic solution and using a physically consistent approach to inserting the field solution into a circuit solution. At this point it is useful to review modified nodal admittance (MNA) analysis. MNA analysis was developed to handle elements that do not have admittance descriptions. For these offending elements additional equations are added to the nodal admittance equations and these equations become additional rows and columns in the evolving matrix system of equations. A similar approach can be followed for the electromagnetic elements. The process is a little more sophisticated, it no longer sufficient to add additional rows. Instead the concept of local reference nodes was developed [7] based on the earlier compression matrix approach [16]. This concept provides another way to incorporate alternate equations in the evolving MNA matrix. However, rather than adding additional constitutive relations, the local reference node concept changes the way the port-based parameters are used. The process begins by dividing and conquering. The first decision is that the nonlinear circuit should be the point of integration. Figure 4 shows a circuit with a spatially distributed circuit and with a global reference node indicated by the conventional inverted triangle symbol. In a conventional circuit only one reference node (ground) is possible so that KCL is applied to the currents in the red dotted oval of Figure 4. This global reference node introduces one additional redundant row in the indefinite form of the MNA matrix. With the local reference node concept shown in Figure 5 with the local reference nodes indicated by the diagonal symbol, KCL is applied to one locally referenced group at a time. The local reference nodes are not electrically connected and so KCL applied to each of the locally referenced groups, here M, results in M redundant rows in the MNA matrix. Modifications to standard circuit theory are required to handle this situation [7]. The local reference node concept is the nodal equivalent of the reference terminal of a group of ports.

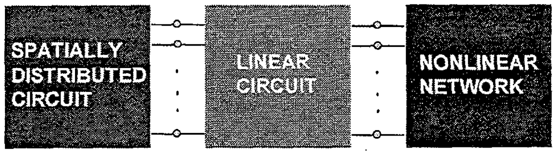


Figure 3. Partitioning of a system into a spatially distributed part, a linear circuit part and a nonlinear network part.

III. STEADY-STATE CASE STUDY: A GRID AMPLIFIER

One of the benefits of modelling and characterization is the physical insight that is gained. An example will be presented in this section. Figure 6 shows a quasi-optical grid amplifier with input and output horns and here 4 unit amplifiers located at the intersection of horizontal and vertical grid lines. (Correlation of measured and simulated nonlinear performance was presented previously [15].) The horizontal lines act as the input antennas of the amplifiers and the vertical lines are the output radiators. In the originally constructed amplifier, Figure 7(a), the simulated field profile of Figure 7(b) was found. In the modified amplifier of Figure 9(a) with closer attention paid to circuit symmetry the field profile of Figure 9(b) was calculated. Note that the beam is not centered in the original circuit but is centered in the modified circuit. Similar beam centers were also found experimentally. Simulation of larger grid structures indicated another cause of non-ideal performance resulting from geometric (or grid) symmetry and circuit symmetry which are incompatible with each other. The solution is to embed groups of unit cells in larger unit structures to more closely approximate common grid and circuit symmetries.

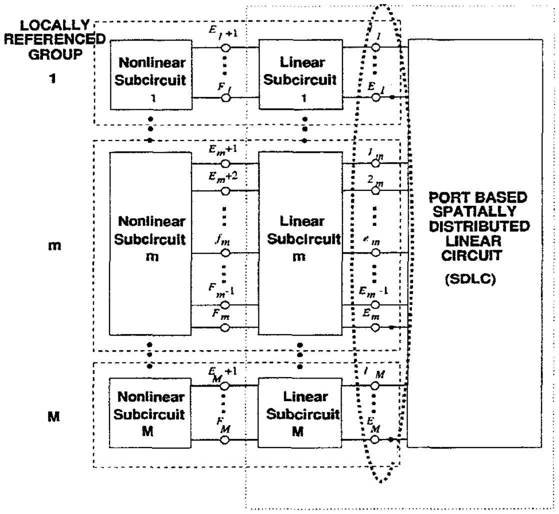


Figure 4. A conventional circuit with a single global reference node.

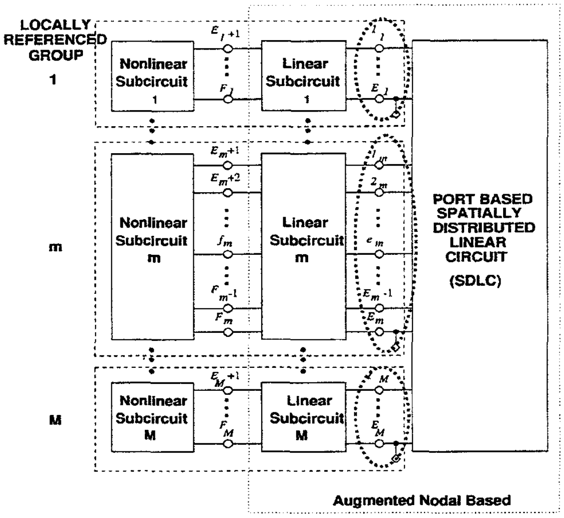


Figure 5. A circuit with local reference nodes.

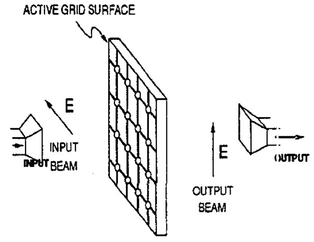


Figure 6. A quasi-optical grid amplifier between an input and output horns.

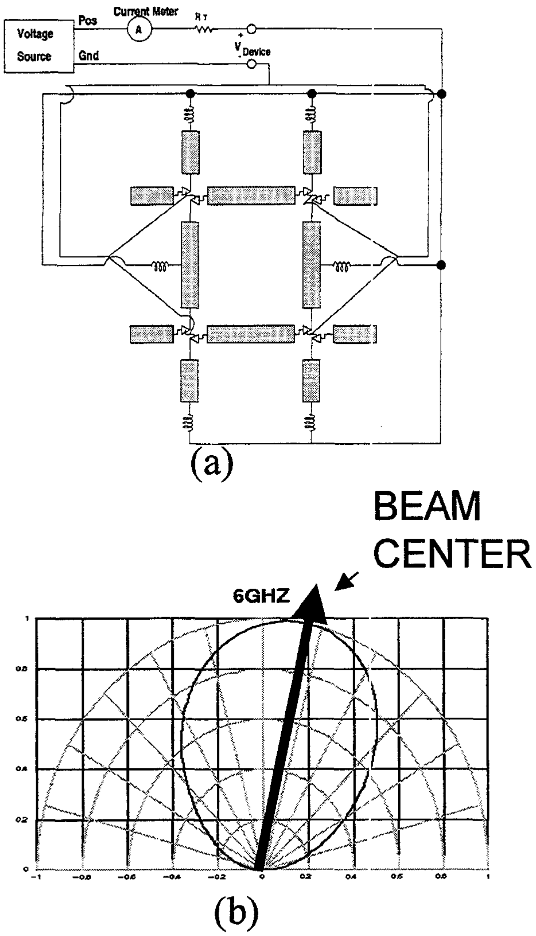
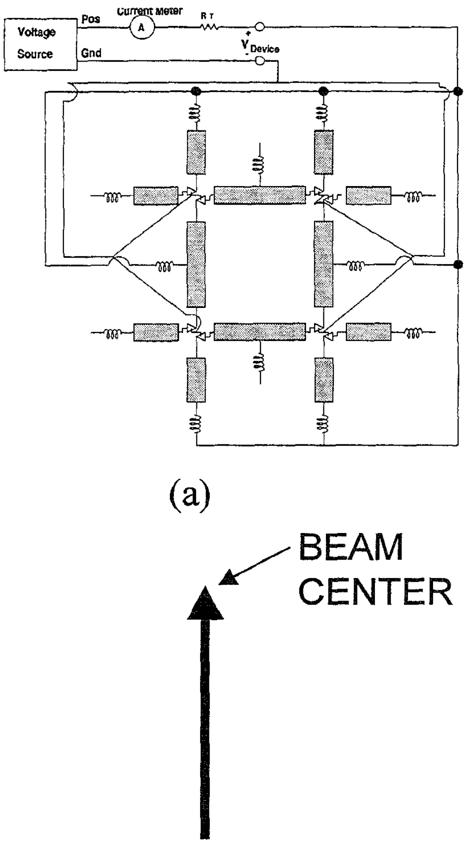


Figure 7. Calculated field profile of a 2x2 grid amplifier with "non-ideal" symmetry.



(a)

(b)

Figure 8. Calculated field profile of a 2x2 grid amplifier with corrected symmetry: (a) circuit schematic and (b) calculated field profile.

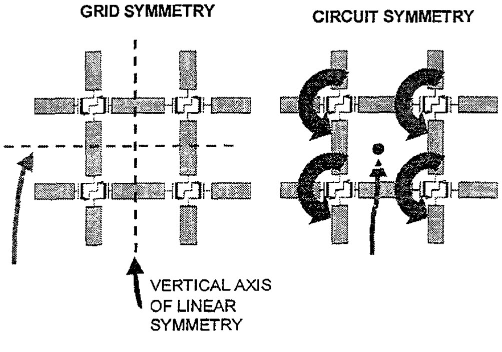


Figure 9 . Grid and circuit symmetry in a grid amplifier.

IV. TRANSIENT CASE STUDY: NONLINEAR TRANSMISSION LINE

In the previous example a method of moments field solver was used to characterize the electromagnetic environment. Method of moments analysis is attractive as it naturally produces port-based parameters. Integration of the port-based parameters works, in general if state-variables are implemented as unknowns in the circuit solver. This has been achieved in steady-state (harmonic balance) solvers for some time but only recently has this been implemented in a transient solver. In our analysis of quasi-optical systems and nonlinear transmission lines we use a convolution of the impulse response of the linear network parameters with the current-voltage relations of an active device. The impulse response is obtained as the inverse Fourier transform of the frequency domain parameters. It is crucial that the this domain-to-domain conversion be physical. This means that the response be frequency limited (in the frequency domain linear circuit characterization) and time-limited (in the equivalent time-domain characterization). One way of achieving this is shown in Figure 10, where absorbing elements (resistors) are used to damp the transient response, and reactive elements are used to bandlimit the frequency domain response. Furthermore delay modification is required to zero the imaginary response at F_{MAX} (or use Hilbert transforms) so that aliasing is controlled [17]. The effect of the lossy elements and of the additional delay is removed during subsequent transient iteration. Measured and calculated responses of a 47 diode nonlinear transmission line are shown in Figure 11.

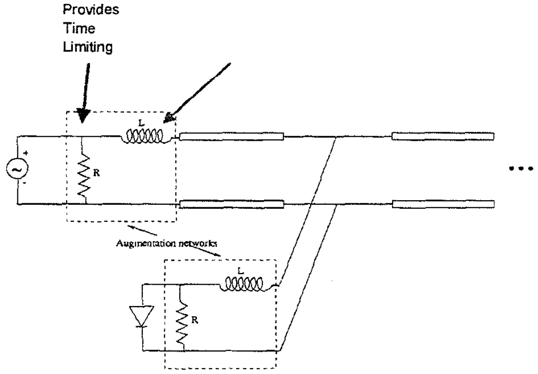
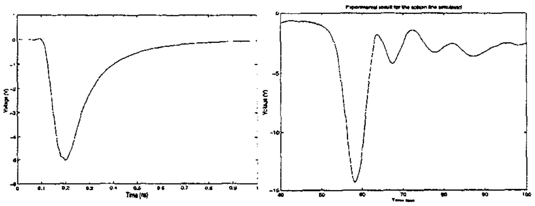


Figure 10. Strategies for controlling domain-to-domain transformation.



(a) (b)

Figure 11. Response of a nonlinear transmission line at diode number 47 : (a) simulated results and (b) measured result.

V. CONCLUSION

The modeling of high frequency systems integrating electromagnetic field characterization with circuit characterization has been shown to be entirely do-able. Considerable attention must be paid to the interface to ensure that the connection of different solution domains is physically correct. The same is true of domain-to-domain conversions. Several key concepts have been developed to facilitate the integrated analysis: 1) the local reference node concept; 2) impulse response/convolution using state variables; 3) frequency limiting using physical elements for aliasing control; 4) time limiting and 5) delay modification.

VI. ACKNOWLEDGEMENTS

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