Application of Quasi-Static Method of Moments for the Design of OC-192 and OC-768 Fiber Optic Integrated Circuits

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Abstract — **A novel global layout modeling technique based on a quasi-static Method of Moments (MoM) analysis [1, 2] for the design of 10 and 40 Gbit/sec Fiber Optic Integrated Circuits is presented. Theory of the quasi-static MoM technique is reviewed and validated for millimeter wave applications. This technique enables rigorous circuit/layout co-simulation with minimum computational resources compared with traditional Electromagnetic solvers. Excellent agreement between simulated and measured results is found in both time and frequency domains.**

I. INTRODUCTION

With the recent advancements in computer-aided design (CAD) technology, design simulation becomes a necessity for today's microwave (MW) and millimeter wave (mmW) Integrated Circuit (IC) designs. Besides operating at MW and mmW frequencies, those designs are fairly complex. Accurate prediction of circuit performance before fabrication becomes a must for shortening design cycles and lowering engineering cost. High-speed digital fiber optic integrated circuits, such as OC-192 (10 Gbit/s) and OC-768 (40 Gbit/s) are broadband circuits. They operate at frequencies ranging from the kHz range to a minimum 10 GHz and from kHz range to a minimum 40 GHz, respectively. Such bandwidths are required to maintain low signal distortion levels. Therefore, accurate design simulations not only rely on the accuracy and robustness of transistor models, but also the passive layout models. That is due to the parasitic inductance, transmission line effects of the interconnections, and resonance of capacitors and inductors above microwave frequencies. Recently, several papers described the application of electromagnetic (EM) analysis tools for the design of the layouts in millimeter wave integrated circuits [3-4]. However, these applications are limited to circuits of low complexity or periodical structures. For complicated circuits, the parasitic extraction method is widely applied to model the layouts of complicated IC's, that provides fast results and reasonable accuracy. However, it is difficult for parasitic extraction tools to model the resonance of capacitors and inductors at microwave frequencies, transmission line effects, and the air-bridge crossover capacitance [5]. Incomplete consideration of layout effects may result in peaking and sagging in the bandwidth of wideband circuits. In this paper, a global layout modeling technique is presented, which is based on the 2.5-D planar quasi-static Method of Moments (MoM) [1, 2]. The theory of quasi-static MoM [1] is reviewed and validated experimentally for its effectiveness for mmW IC designs. Comparative analyses of quasi-static MoM and conventional MoM approaches including convergence speed enhancements and computational requirements are also presented. The global layout analysis method in conjunction with Vertical bipolar inter-company (VBIC) transistor models is applied to a complicated 10-Gbit/s broadband amplifier. Excellent agreements between simulated and measured results are observed in both frequency and time domains.

II. FORMULATION OF QUASI-STATIC METHOD OF MOMENTS

The quasi-static Method of Moment technique is reported in [1], and the methodology is adopted in Agilent's EEsof Momentum RF [2]. In this section, the theory of quasi-static MoM is briefly reviewed for completeness. This review is an expansion from the work presented in [1]. This method is based on Mixed Potential Integral Equations. The relationship between Mixed Potential Moment Matrix ($[Z(\omega)]$) and the unknown currents $|I(\omega)\rangle$ can be expressed as

$$[Z(\omega)]|I(\omega)\rangle = |V(\omega)\rangle \tag{1}$$

where $|V(\omega)\rangle$ is the voltage impressed by the sources or subject to the boundary conditions. The Moment Matrix can be re-expressed as

$$[Z(\omega)] = [R(\omega)] + j\omega[L(\omega)] + 1/j\omega[C(\omega)]^{-1} \tag{2}$$

where $[R(\omega)]$, $[L(\omega)]$, and $[C(\omega)]$ represent the frequency dependent resistance, inductance, and capacitance matrices, respectively. A full-wave MoM can be developed based on equations (1) and (2). The explicit forms of the elements in $[R(\omega)]$, $L[(\omega)]$, and $[C(\omega)]$ matrices can be expressed in equations (3)-(5).

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$$Z_{ij}^{R} = R_{ij}(\omega) = Z_S(\omega) \iint_{S_i} ds \iint_{S_j} ds' \, \delta(\mathbf{r}-\mathbf{r}') \, \mathbf{B}_i(\mathbf{r}) \cdot \mathbf{B}_j(\mathbf{r}') \tag{3}$$

$$Z_{ij}^{L} = j\omega L_{ij}(\omega) = \iint_{S_i} ds \iint_{S_j} ds' \, \mathrm{G}_m(\omega, \mathbf{r}-\mathbf{r}') \, \mathbf{B}_i(\mathbf{r}) \cdot \mathbf{B}_j(\mathbf{r}') \tag{4}$$

$$Z_{ij}^{C} = 1/j\omega C_{ij}(\omega) = \iint_{S_i} ds \iint_{S_j} ds' \, \mathrm{G}_e(\omega, \mathbf{r}-\mathbf{r}') \, \nabla \cdot \mathbf{B}_i(\mathbf{r}) \, \nabla \cdot \mathbf{B}_j(\mathbf{r}') \tag{5}$$

where G(ω, **r-r'**) and **B(r)** are the Green's and the basis functions, respectively. The Green's function can be expressed in a Taylor series as:

$$G(\omega, \mathrm{r}, \mathrm{r}') = e^{-jkR}/R = \frac{1}{R}\left(1 - jkR - (kR)^2/2! \, \ldots\right) \tag{6}$$

where k is the free-space wave number and $R = |\mathrm{r}-\mathrm{r}'|$. At low frequencies or when the structures are electrically small, the higher order terms in (6), that govern radiation, can be ingored. The quasi-static Green's functions can be expressed as

$$G(\mathrm{r}, \mathrm{r}') \approx \frac{1}{R} \tag{7}$$

Based on (7), equations (4) and (5) can be simplified to frequnecy scalable expressions. Therefore, the Moment matrix equation (2) can be simplified as:

$$[\mathrm{Z}(\omega)] = [\mathrm{R}(\omega)] + j\omega[\mathrm{L}] + 1/j\omega[\mathrm{C}]^{-1} \tag{8}$$

Instead of re-computing the entire Moment Matrix at each frequency, equation (8) provides a scalable Moment matrix, which greatly reduces the computational time. Instead of using rooftop basis functions, the loop and star basis functions are adopted to ensure low frequency stability and enable mesh reduction [1,2]. These features ensure shorter computational time and less memory requirements for complicated structures, in comparison with traditional 2.5-D full-wave MoM.

III. Global Layout EM Modeling Techniques

Because the 3-D EM effects in IC interconnections and passive elements are negligible, a 2.5-D planar EM solver is a more efficient tool for a complex IC shown in Fig.3. The quasi-static MoM provides faster results and requires less memory, which enables EM modeling of complex IC layouts. The layout simulation is done using Agilent's Momentum RF and is exported into Agilent's Advanced Design System (ADS) for circuit/layout co-simulation. By setting up the layer mapping files, the IC layout can be transferred between the layout tool and the EM simulator via GDSII or other layer mapping files. When importing a layout into Momentum, all of the transistors and resistors are removed and modeled in the circuit simulator (ADS). VBIC and transmission line models are used for the transistors and resistors, respectively. For computational efficiency, the layout models are partitioned based on the coupling effects between the circuit stages and elements. However, it is inadequate just to partition the layout based on the boundaries of circuit functional stages. One has to look at the coupling effects between various stages due to layout proximity. For this, the visualization tool is an excellent vehicle for tracing the lines of minimum coupling. This coupling analysis is done using a global current visualization of a layout section using a low meshing density (shown in Fig. 4). This provides fast first order results for the coupling effects. The partitioned layout models are simulated with fine meshing resolution. For modeling IC passive circuitry and interconnections, the meshing frequency and density need to be higher than those for the RF board and antenna applications in order to generate adequate current samples. Multiple S-parameter layout models with layout look-alike symbols are placed in the circuit simulator. Layout lookalike symbols make it easier to integrate the EM and circuit tools.

IV. Validation for Microwave IC Applications

In this section, the validation of the quasi-static MoM is presented. Two 1.9-mm coplanar waveguides are printed side by side with a 50-um separation on an Indium Phosphide (InP) wafer, shown in Fig. 1. The electrical lengths of waveguides are similar to those of typical traveling wave amplifiers (TWA) for OC-768 applications. The effectiveness of the quasi-static MoM for millimeter Wave applications is observed (Fig. 2). The spikes in S-parameter magnitude measurements and simulations, found at 24 and 28 GHz, are caused by higher order modes and by the resonance coupling from the un-terminated waveguides positioned 50-um away, which is confirmed by inspecting the magnitudes and phases of the measured S-parameters of both waveguides. However, the resonances in the measurements are weaker than those in simulations. The effectiveness of the quasi-static MoM is validated. Table I shows the convergence of Z_o and R_{dc} as a function of meshing desnsity using Quasi-static MoM. Table II shows the required computational resources of the quasi-static MoM. Fast convergence and minimum computational requirements are observed compared with full-wave MoM. The quasi-static MoM requires 40% to 90% of the memory needed by the conventional 2.5 D MoM and simulates the circuit in 1/8 to 1/6 of the time.

The global layout analysis in conjunction with VBIC transistor models and transmission line resistor models is applied to a 10 Gbit/s fiber optic amplifier (Fig. 3). The layout model partitioning analysis is applied to the circuit layout. Cross-talk analysis of a gain-stage layout is shown in Fig. 4. It indicates low cross-talk between the two transistor arrays and hence the possibility of dividing this layout into two localized models. Small signal validation is verified by comparing the magnitudes of the measured and simulated S-parameter results of the entire circuit, which is shown in Fig. 5. Excellent agreement is observed. Large signal validation is verified by comparing transient simulation and measurement using eye diagrams, which is shown in Fig. 6. Good agreement in rise time, fall time and transient waveform is observed.

V. Conclusion

A novel global layout modeling technique based on quasi-static MoM for complex IC designs is presented. This technique reduces the required memory size and decreases the simulation time by a factor of 6. Due to low radiation effects in MW IC's, excellent agreement between simulated and measured results is observed. The theory of quasi-static MoM [1] is reviewed and its effectiveness and efficiency for microwave and millimeter wave IC applications is presented.

Acknowledgement

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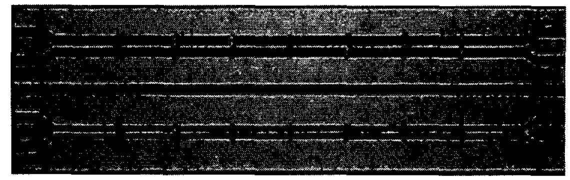


Fig.. 1. InP coplanar waveguides for OC-768 (40 Gbit/s) applications.

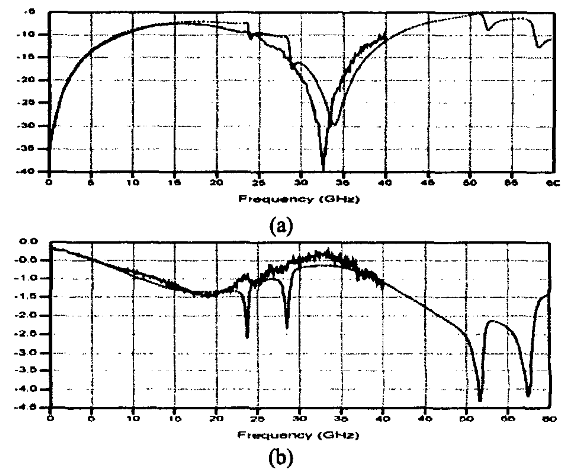


Fig. 2. Measurements (solid line) versus quasi-static MoM simulations (dotted line) (a) Return Loss (dB). (b) Insertion Loss (dB).

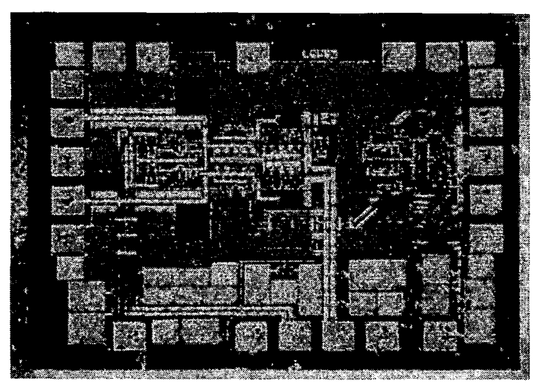


Fig. 3. OC-192 (10 Gbit/s) GaAs Amplifier.

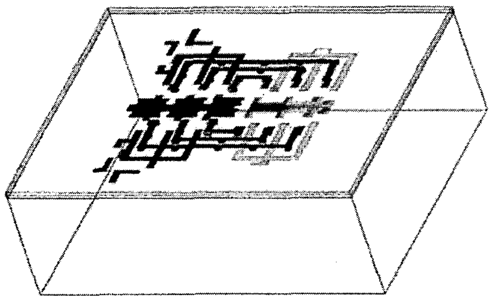
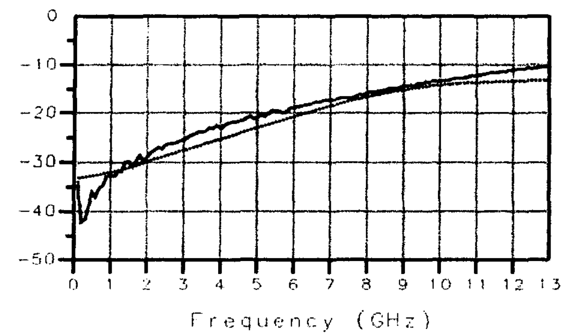
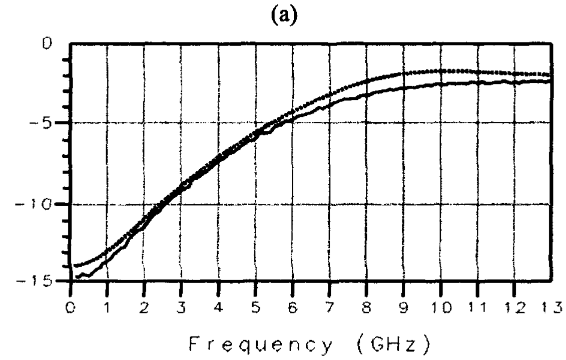


Fig. 4. Global visualization of induced currents between interconnections for the localization of layout modeling.



(a)



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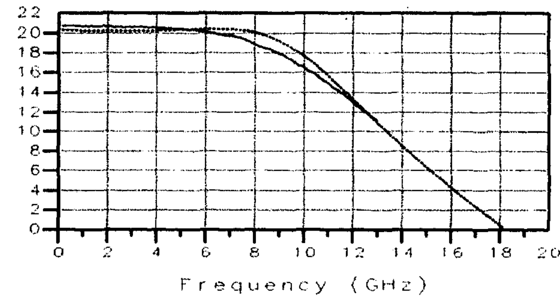
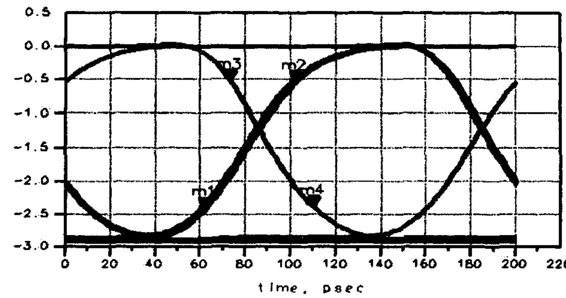
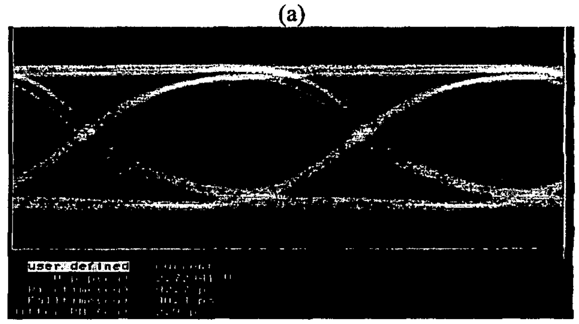


(c)

Fig. 5. Measured (solid line) versus simulated (dotted line) magnitudes of S-parameters for the OC-192 amplifier in Figure 3. (a) S11 (dB), (b) S22 (dB), and (c) S21 (dB).



(a)



(b)

Fig. 6. Eye diagram of the 10Gbit/s EAMD. (a) Simulated eye diagram, (b) Measured eye diagram.

Table I. Convergence Test of Quasi-static MoM.

Mesh Density (cell/λ @ 40 GHz)	5	15	25	50
Zo @ 40 GHz (Measured Zo = 70.6 Ω)	72	69.7	69.2	69.1
R @ DC (Measure R = 2.02 Ω)	2.3	2.29	2.20	2.12

Table II. Quasi-Static MoM (RF) versus Full-wave MoM (MW) in Required Computational Resources on a 450 MHz Workstation.

Mesh Density (cell/λ @ 40 GHz)	5		15		25		50	
Type of MoM	RF	MW	RF	MW	RF	MW	RF	MW
Unknowns	1516	3054	1898	3515	2570	4332	4771	6988
Memory (MB)	90.37	216.65	119.98	218.60	195.69	269.75	416.91	488.64
CPU Time (min)	61.25	550.03	95.05	761.32	197.97	1300.53	785.74	4304.8