Progress In Electromagnetics Research B, Vol. 22, 171–185, 2010

ON-CHIP TECHNOLOGY INDEPENDENT 3-D MODELS FOR MILLIMETER-WAVE TRANSMISSION LINES WITH BEND AND GAP DISCONTINUITY

G. A. Wang, W. Woods, H. Y. Ding, and E. Mina

IBM Semiconductor Research and Development Center
1000 River Street, Essex Junction VT 05452, USA

Abstract—Although the discontinuity structures in the microstrip transmission lines such as a gap and bend have been largely studied, the three-dimensional edge effects, skin effects and metal losses have hardly been analyzed. In this paper, modeling of transmission line with bend and gap discontinuity with equation based process technology independent method are developed. The effect of the signal layer thickness is fully included in the model. Gap model is verified with EM simulation and implemented in BiCMOS technology on Silicon substrate. The bend is modeled with transmission line with effective length for the discontinuity area, and the equations have been generated. The bend model is compared with EM simulations, existing bend model generated with curve-fitted method and measured results. Gap and bend are enabled as library device in a 0.13 μm SiGe BiCMOS process design kit. Both bend and gap device have a scalable layout pattern and a schematic symbol, which allows users to choose them with different dimensions and metal stacks. In addition, the models can be migrated into other process technologies with different metal options. Very good match have been achieved among model, EM simulation and measurements for different process technologies and metal stacks.

1. INTRODUCTION

Microstrip transmission lines have been widely used as fundamental structures for the development of microwave integrated circuits. The bend and gap are used widely in both hybrid and monolithic circuits. Extensive research on the filter design using gap discontinuity have been studied due to the importance of the end-to-end coupling of

---

Corresponding author: G. A. Wang (gawang@us.ibm.com).

resonators in strip and microstrip lines [1–3]. It has also been a common practice in the millimeter wave designs to use transmission lines and other interconnect shapes, such as bends and tees, to count the layout parasitics for critical signal paths. A great deal of work has been published on the properties of the microstrip transmission line and its discontinuity such as bend and gap [4–6]. The gap has been analyzed predominately by quasi-static methods [6, 11], the results of which used extensively in computer-aided design routines. Fully electromagnetic solutions have been calculated by Jasnsen and Koster [12] using a spectral-domain method. However, none of them considering the 3D effect of the transmission line such as metal thickness and layout asymmetries. For Radio Frequency (RF) components, the thickness of the transmission line which is comparable to the dimension of discontinuity, its effect is getting very important and needed to be considered in the model for accurate results.

With the development of high speed transistor and wireless personal area wireless network and directional link applications, the enhanced scaling down of the size, the crosstalk among the high density interconnects at high frequencies is getting more and more serious and causing degradation on the RF signal, it is critical to predict the coupling between interconnects with an accurate model. Accurate active and passive models are required for the design of circuits operating near the frequency limits of a given technology. At higher frequencies, layout-dependent parasitics include not only the capacitance and resistance parasitics, but also the inductance parasitics, which could be neglected at lower frequencies. It is very important to get accurate characterization of passives on lossy silicon substrates, like transmission lines, inductors and capacitors etc., which can be used as resonators, matching networks and bias circuits.

One of the crucial factors for a successful design is the accurate active and passive models which designers can use. Although some research have been done on EM modeling for microwave components [7], most designers have to run their own electromagnetic simulations to generate models for the layout parasitics, because of the lack of supported models in a design kit for the layout parasitics. These customized parasitic models normally are not scalable and may have issues with the design rule check (DRC) and the layout versus schematic (LVS) check in a design automation environment. Recently a set of distributed passive devices, such as bends and tees, have been developed and added into an IBM 0.13 μm BiCMOS design kit for millimeter wave applications under the Cadence design environment [8, 9]. But unfortunately, the current models are generated using curve-fitted method which is very time-consuming, and it can not be migrate into other process technologies without further simulations and fittings. The idea to generate technology independent model for gap has been introduced and presented in [10].

This paper presents equation-based process technology independent models for transmission line with bend and gap discontinuity. 3-D edge effects, skin effects and metal losses of the transmission line have been analyzed, and library devices have been developed for bend and gap based on the model with schematic symbol and parameterized cell. Both symmetrical and asymmetrical gap structures (transmission lines on both sides of the gap have the same or different widths) have been modeled based on equations generated. The equations calculating equivalent length of the bend discontinuity area are provided, and the bend is modeled with existed single transmission line models with the calculated equivalent length. Since the models are built based on equations, they can be extended and have been verified in different process technologies. The models are verified by EM simulation with Ansoft HFSS, current curve fitted model and measurements from implemented transmission lines in 0.13 μm BiCMOS technology. Good match have been achieved for both models. The models can be used to design passive components to dramatically reduce design cycle with the developed schematic symbol, PCell and model. The implemented transmission lines are developed at top metal level in the back end of the line (BEOL) with bottom shield to minimize the effects of the lossy silicon substrate.

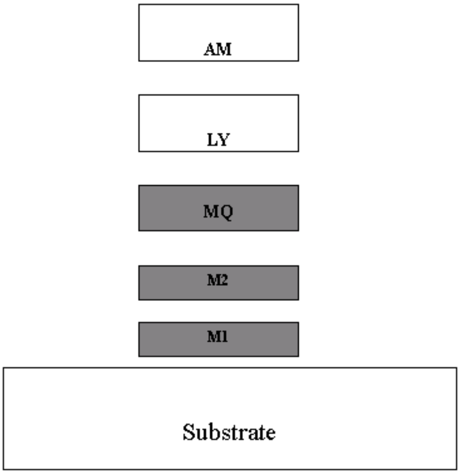

Figure 1. Cross section of metal layers in a BiCMOS technology.

The BEOL stack in this 0.13 μm BiCMOS technology has two thin copper layers (M1-M2), one thick copper layer (MQ), and two top aluminum layers (AM and LY), see Figure 1. The total thickness of the silicon dioxide dielectric between the top metal layer and bottom layer is about 15 μm, and the silicon resistivity is around 10 Ω-cm.

2. MODEL IMPLEMENTATION FOR A GAP

2.1. Structures and Equations

Figure 2 shows two transmission lines with different width separated by a gap. The transmission lines have the same thickness and common ground shield layer. In this paper, the signal layer of the implemented transmission line with gap is the thick aluminum layer. Figure 3 shows the equivalent circuit model for the transmission line with gap discontinuity. The model includes several capacitors and single transmission line models developed at IBM. The transmission line model include resistor, inductor and capacitors, skin effect and losses of the metal are considered. Figure 4 shows the capacitors due to the edge effects of each transmission line and the ground layer at the gap, and Figure 5 shows the coupling capacitors between the two transmission lines across the gap.

In the figure, capacitors between the transmission line and the ground due to the edge effect of the gap is the sum of 4 different capacitors which are the results of the coupling between the ground and two lateral sides, the top side and the bottom side of the 3-Dimensional transmission line end. The capacitor across the gap

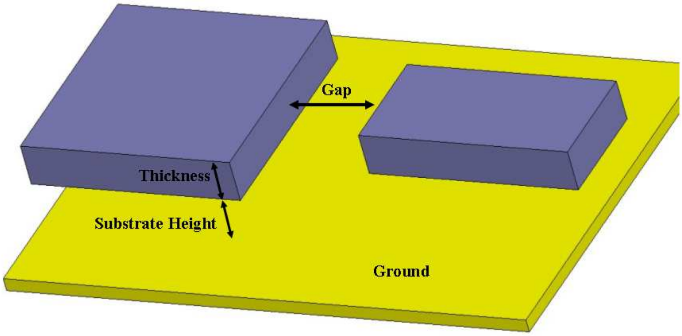

Figure 2. Schematics of transmission line with gap.

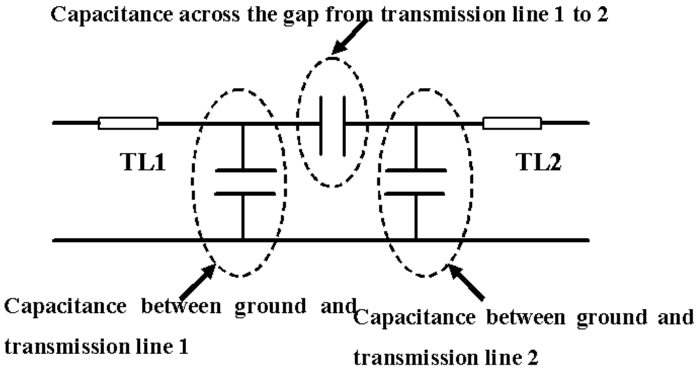

Figure 3. Equivalent circuit model of transmission line with gap.

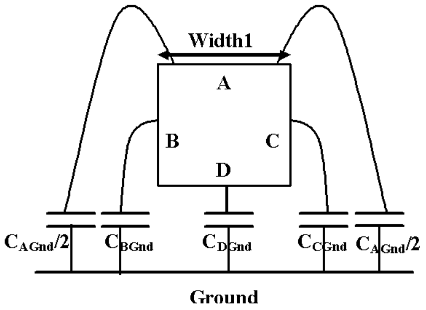

Figure 4. Capacitors between the ground and the edge of left/right transmission line.

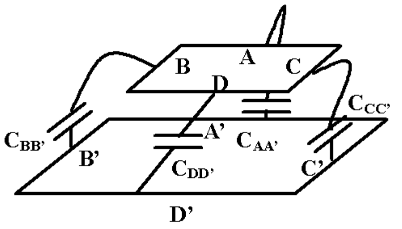

Figure 5. Capacitors between the edge of transmission lines across the gap.

includes 4 capacitors due to the edge coupling between the transmission lines and the face coupling which can be calculated by standard capacitor calculation equations. The capacitances of the elementary terms are described in [13]. To count the effect of the metal thickness, the equations from [13] were modified, fitted and used to build the model. Equations are fitted and verified with EM simulation and current IBM curve-fitted gap model. For transmission line without side shield, the capacitor between the bottom ground shield and the gap Cgnd is described by Equation (1) and the coupling capacitor across the gap C_{12} is described by Equation (3).

$$C_{gnd} = C_{gnd1} + 2tgC_{Cgnd}g/(0.5t + h + g) \tag{1}$$

$$C_{gnd1} = wg(C_{Agnd}/(t + h + g) + C_{Dgnd}/(h + g)) \tag{2}$$

$$C_{12} = C_{c1} + 2tgC_{CC'}(h + 0.5t)(g + 0.5t)/((0.5t + h + g)h) \quad (3)$$

$$C_{c1} = 2wh(C_{AA'}(g + t)/((t + h + g)h) + C_{BB'}g/((2h + g)h)) \quad (4)$$

where g is the gap distance, t is the metal thickness, w is the width of the transmission line and h is the substrate height. The equations have been verified for gap distance from 0.1 µm to 50 µm, t from 0.1 µm to 10 µm, w from 0.5 µm to 50 µm.

The developed design model in this paper for the transmission line with gap discontinuity can be scaled for different gap distance, different transmission line width and different metal combinations for different process technologies. With the developed existing transmission line model, this gap model can be used for edge coupled filter design, interconnect analysis at different frequencies and any other passive components design with gap included.

2.2. Implementation and Measurement Results

To verify the developed gap model, EM simulations of the transmission line with different width and gap distance have been done first with Ansoft HFSS. Equivalent circuit model as shown in Figure 3 was simulated in Cadence analog environment. Capacitors are calculated considering all the side coupling and other parasitic effects. and the implemented transmission line with gap were also measured. Results were compared and plotted together.

Comparison between EM simulation and model results for transmission line with width from 4 µm to 50 µm, while the gap ranges from 2 µm to 13 µm have been done. Figure 6 shows the results comparison for transmission line with 16 µm width on both sides of the gap, the gap is 7 µm. At 100 GHz, the phase difference is 0.1° for coupling and 0.1° for return loss, while the return loss magnitude has the difference of 6 mdB and the coupling has 1.4 dB difference. When both the transmission lines have the width of 16 µm and the gap is 4 µm, the results comparison is shown in Figure 7. Good match has been achieved with less than 0.1° phase difference for both return loss and coupling loss, while the return loss difference is only 13 mdB and coupling loss difference is 0.5 dB, in addition, good correlation between the hardware measurement and model is achieved as shown in the figure. Model for gap of transmission line with side shield is also developed in this paper.

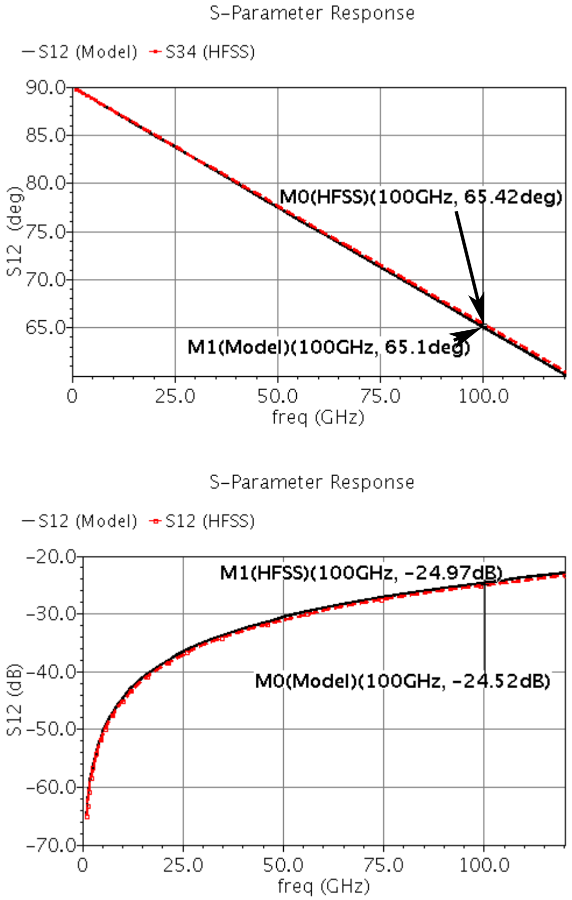

Figure 6. Phase (top) and Magnitude (bottom) results comparison of insertion loss between EM simulation and model for $W_1 = 16\,\mu\text{m}$, $W_2 = 16\,\mu\text{m}$ and gap $= 7\,\mu\text{m}$.

3. MODEL IMPLEMENTATION FOR A BEND

3.1. Structures and Equations

Figure 8 shows the structure of a microstrip transmission line with bend. In this paper, equations have been developed to calculate the equivalent length of the bend discontinuity area, and the bend discontinuity area is replaced using the existed transmission line model with the calculated equivalent length. The existed transmission line

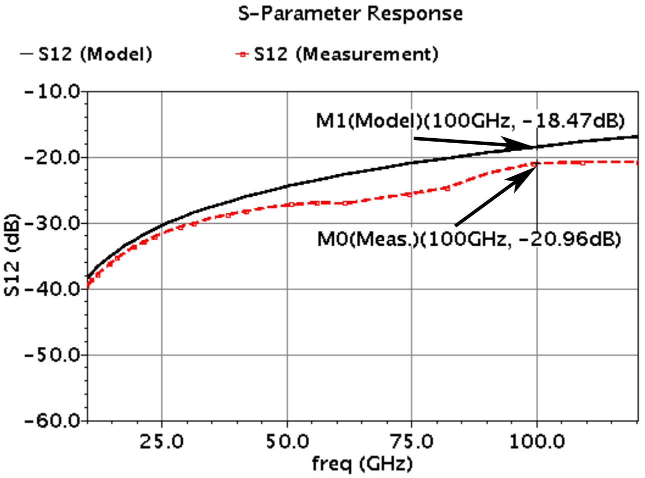

Figure 7. Insertion loss magnitude results comparison between EM simulation, measurement and model for $W_1 = 16\,\mu\text{m}$, $W_2 = 16\,\mu\text{m}$ and gap $= 4\,\mu\text{m}$.

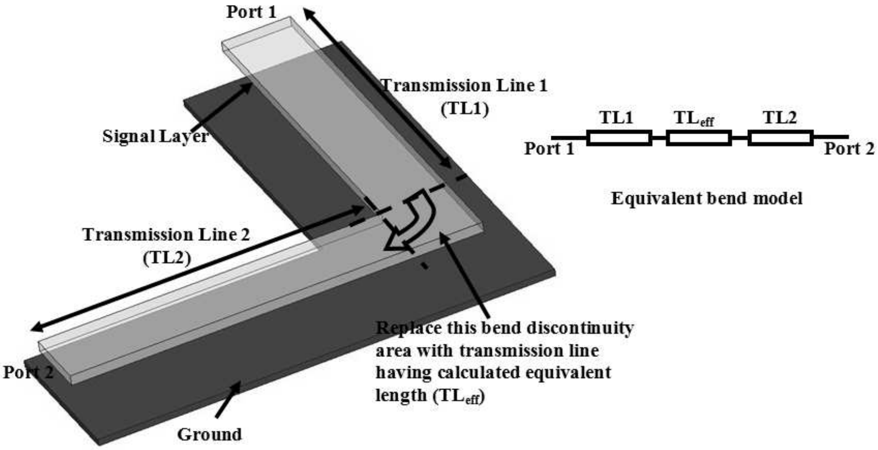

Figure 8. Schematics of transmission line with bend.

model is described with frequency dependent R, L and C network, skin depth, metal losses and metal thickness effect are thoroughly considered in the model. The signal layer of the implemented meander line with bend is the thick aluminum layer. The meander line is 930 μm long and has 8 bends. Four different type of bends have been simulated and verified, single bend, bend with side shield, bend with miter, and bend with side shield and miter as shown in Figure 9. Equations for equivalent length of the bend areas have been developed for all of the four types of the bends.

The equations for the equivalent length calculation of the bend area were generated through fitted method by compare EM simulations summarized in Table 1 and simulations with transmission line model with equivalent length, the equations are also fitted and verified through current IBM curve-fitted bend model. Equations (5)–(8) describe the equivalent length calculation for bend in structure 1–4 in Figure 9.

$$L_{\mathit{eff}} = 0.48W - H/2 \tag{5}$$
$$L_{\mathit{eff}} = 0.88W - H/2 \tag{6}$$
$$L_{\mathit{eff}} = 0.38W - H/2 \tag{7}$$
$$L_{\mathit{eff}} = 0.62W - 3H/4 \tag{8}$$

where W is the bend width and H is the distance between the signal layer and ground shield. The developed equations are valid for modeling respective bend type as shown in Figure 9. All the cases for W from 0.5 µm to 50 µm and H from 0.3 µm to 20 µm have been verified.

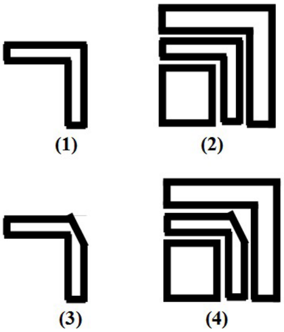

Figure 9. Bend types: (1) single bend, (2) bend with side shield, (3) bend with miter and (4) bend with side shield and miter.

Table 1. Summary of testcases of the developed bend model.

Signal Layer	AM	LY	MQ	M2
Signal Width	4–50 µm	1.5–50 µm	0.5–20 µm	0.5–20 µm
Ground Layer	M1 M2, MQ, LY	M1, M2, MQ	M1, M2	M1

The developed model in this paper for the transmission line with bend discontinuity can be scaled for different transmission line width and different metal combinations for different process technologies. The verification and the migration demonstrations of the developed bend model into other technologies is shown in the next section.

3.2. Implementation and Measurement Results

To verify the developed bend model based on the equivalent straight length calculation equations, the model is simulated and compared with current existed IBM 0.13 µm SiGe technology bend model developed using curve-fitted method. As shown in the developed equations for the equivalent length calculation of the bend discontinuity area, the equivalent length is related with the width of the bend and the distance between the signal and ground layer. Models have been verified with simulations for different width and ground space. Table 1 summarized all the simulation cases. Different metal layers have been used as signal layer, when using thick AM layer as signal layer, the width of the bend varies from 4 to 50 µm, the substrate height H varies from 4 to 10 µm when using different metal as ground; When using thin LY as signal layer, the width of the bend varies from 1.5 to 50 µm, the substrate height H varies from 4 to 7 µm when using different metal as ground; When using thick MQ as signal layer, the width of the bend varies from 0.5 to 20 µm, the substrate height H varies from 0.6 to 1.3 µm when using different metal as ground; When using M2 as signal layer, the width of the bend varies from 0.5 to 20 µm, the substrate height H varies from 0.6 to 1.5 µm when using different metal as ground. Simulation results comparison between the new developed bend model based on the equivalent length calculation and current existed bend model show perfect match for each the testcase as described above, this means that the developed model based on the equations is very accurate for this IBM process technology. Figure 10 shows the simulation results comparison for the new equation based model and current existed model, in this case, the top signal metal is thick copper layer (MQ) and ground shield is thin copper layer (M2), and the width of the bend is 2.5 µm which has the characteristic impedance of 35 Ohm. At 100 GHz, the phase difference between models is 0.1° for insertion loss, while the insertion loss magnitude has the difference of 2.5 mdB.

The developed equivalent straight length calculation for the bend discontinuity area have been used to develop bend model for other technologies. The model is simulated in Cadence spectre environment, and the results are compared with the EM simulation. The bend model in several different technologies have been verified. Figure 11 shows

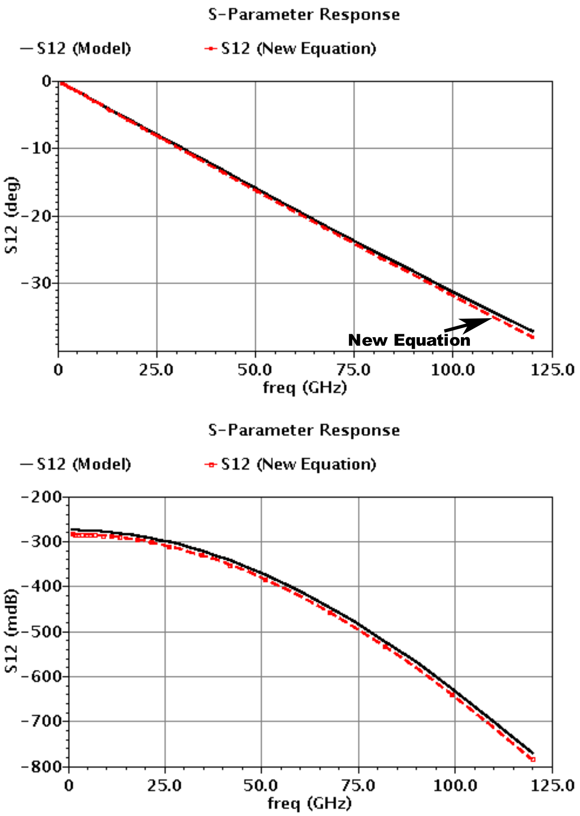

Figure 10. Phase (top) and Magnitude (bottom) results comparison of insertion loss between EM simulation and model for $W = 2.5\,\mu\text{m}$, MQ as signal layer and M2 as ground layer.

the result comparison among EM simulation, new model simulation and current existed bend model simulation, the bend has the signal layer of AM layer with the width of 30 µm and M2 as ground layer which generating of characteristic impedance of 35 Ohm. Very good match have been achieved among all the results, At 100 GHz, the phase difference among the results is 4° for insertion loss, while the insertion loss magnitude has the difference of 0.2 dB.

In addition, the meander line is implemented in the back end of line using IBM 0.13 µm technology, the line is designed with the characteristic impedance of 50 Ohm, while the signal layer is the thick AM layer and the ground layer is M2 layer. The fabricated line is measured with Agilent network analyzer using Thru, Reflect,

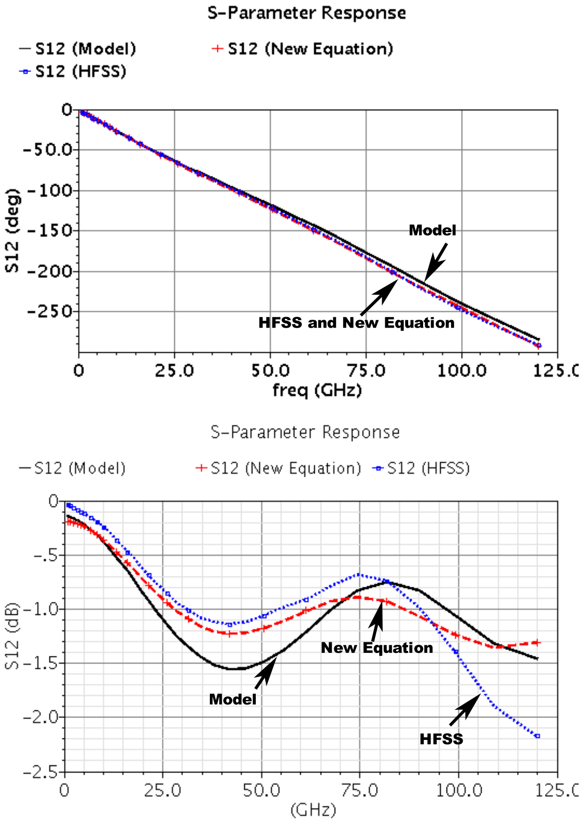

Figure 11. Phase (top) and Magnitude (bottom) results comparison of insertion loss between EM simulation, old model and new model for $W_1 = 30\,\mu\text{m}$, AM as signal layer and M2 as ground layer.

Line (TRL) calibration technique. The results comparison among EM simulation, measurement, new model simulation, current model simulation are shown in Figure 12, At 100 GHz, the phase difference between models is 1° for insertion loss, while the insertion loss magnitude has the difference of 0.1 dB. There is a little bit bigger difference between the model and measurement, this is mostly due to the a little over deembeding during the the measurement.

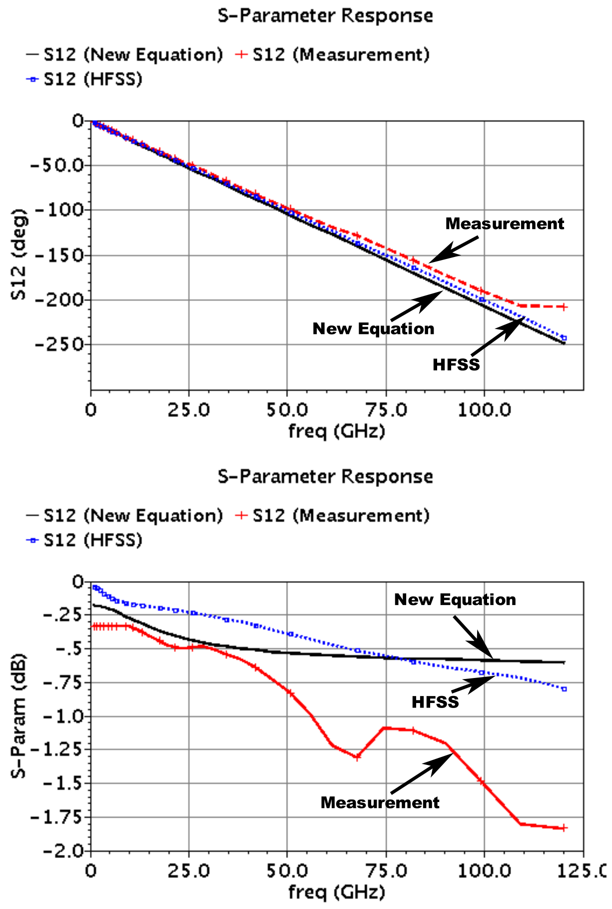

Figure 12. Phase (top) and Magnitude (bottom) results comparison of insertion loss between EM simulation, measurement, old model and new model for $W_2 = 15\,\mu\text{m}$ in a IBM $0.13\,\mu\text{m}$ technology.

4. CONCLUSION

Design models for on chip 3-D transmission line with gap and bend discontinuity are developed, the effect of the signal layer thickness is fully included, and the models are verified with EM simulation and measured results. Very good correlation have been achieved among hardware measurement, model and EM simulation on both the phase and magnitude. A library device for both gap and bend have also provided based on the developed model with PCell and schematic symbol. The developed equation based gap model and the library device are very useful for the design of edge-coupled band pass filters and can be used as a guideline on the layout spacing of the interconnects. Very good correlation have been achieved among hardware measurement, model and EM simulation on both the phase and magnitude for different cases. The developed gap and bend models can be extended for different process technologies, the migration feasibility have been demonstrated in this paper.

ACKNOWLEDGMENT

The authors would like to thanks the support from IBM Semiconductor Research and Development Center.

REFERENCES

1. Yu, P.-C. and K. Chang, "Novel compact elliptic-function narrow band bandpass filters using microstrip open-loop resonators with coupled and crossing lines," *IEEE Transactions on Microwave Theory and Technique*, Vol. 46, 952–958, Jul. 1998.
2. Tzuang, C.-K. C., Y.-H. Chiang, and S. Su, "A compressed-length 90° bend offset broadside-end-coupled bandpass filter," *IEEE Microwave and Guided Wave Letters*, Vol. 1, 285–287, Oct. 1991.
3. Her, M.-L. and C.-M. Chang, "Analysis of slot-loaded end-coupled reasonator CPW bandpass filters," *Proceedings of APMC 2001*, 326–328, Dec. 2001.
4. Silvester, P. and P. Benedek, "Microstrip discontinuity capacitances for right-angle bends, T junctions, and crossings," *IEEE Transactions on Microwave Theory and Technique*, Vol. 21, No. 5, May 1973.
5. Farrar, A. and A. T. Adams, "Matrix methods for microstrip three-dimensional problems," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 20, No. 8, Aug. 1972.
6. Benedek, P. and P. Silvester, "Capacitance of parallel rectangular plates separated by a dielectric sheet," *IEEE Transactions on Microwave Theory and Technique*, Vol. 20, 504–510, Aug. 1972.
7. Mohammadi, F. A. and M. C. E. Yagoub, "Electromagnetic model for microwave components of integrated circuits," *Progress In Electromagnetics Research B*, Vol. 1, 81–94, 2008.
8. Ding, H. Y., G. A. Wang, K. Lam, D. Jordan, A. Zeeb, A. Bavis, E. Mina, and B. Gaucher, "Modeling and implementation of on-chip millimeter-wave compact branch line couplers in a BiCMOS

technology," *2007 European Microwave Conference*, Munich, Germany, Oct. 2007.

9. Ding, H. Y., K. Lam, E. Mina, J. Rascoe, D. Jordan, A. Zeeb, and B. Gaucher, "On-chip millimeter-wave library device — Scalable Wilkinson power divider/combiner," *Proceedings of 2006 ECTC*, Reno, Nevada, 2006.
10. Wang, G. A., H. Y. Ding, A. Bavisi, K. Lam, and E. Mina, "On-chip 3-D model for millimeter-wave T-lines with gap discontinuity in BiCMOS technology," *Proceedings of Asia-Pacific Microwave Conference 2007*, 631–634, 2007.
11. Gopinath, A. and C. Gupta, "Capacitance parameters of discontinuities in microstrip lines," *IEEE Transactions on Microwave Theory and Technique*, Vol. 26, 831–836, Oct. 1978.
12. Jansen, R. and N. Koster, "A unified CAD basis for the frequency dependent characterization of strip slot and coplanar MIC components," *Proceedings of 11th European Microwave Conference*, 682–687, Oct. 1981.
13. Stellari, F. and A. Lacaita, "New formulas of interconnect capacitances based on results of conformal mapping method," *IEEE Transactions on Electron Devices*, Vol. 47, No. 1, 222–231, 2000.