

IEEE CAT. NO. 99CH36282

Copyright Reg. ISSN 0149-645X



# 1999 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST

Volume 1

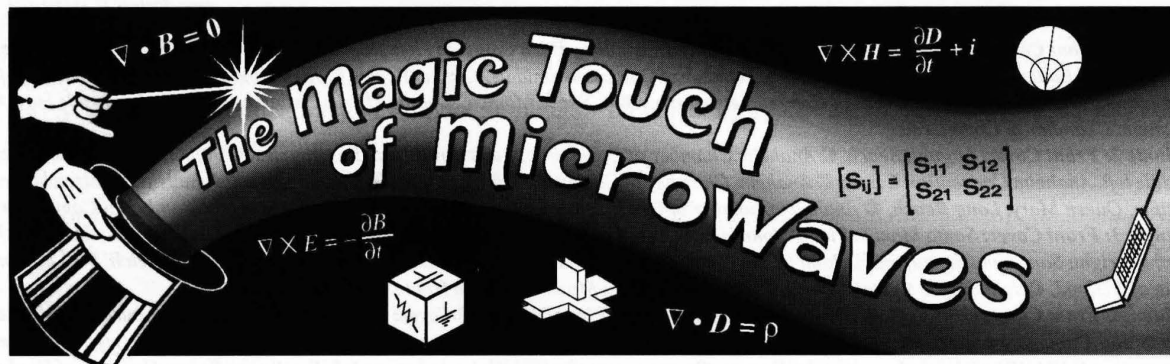
June 13 - 19, 1999  
Anaheim Convention Center  
Anaheim, California

Digest Editor  
Mehran Matloubian

Co-Editor  
Elmira Ponti

CD-ROM Editor  
Debabani Choudhury

**1999 IEEE MTT-S International Microwave Symposium**



JUNE 13-19, 1999 • ANAHEIM CALIFORNIA

*Responsibility for the contents of the papers published in this Digest rests upon the author and not upon IEEE or any of its members.*

***Additional copies of this Digest are available from,***

*The Institute of Electrical and Electronic Engineers, Inc.  
Publication Order Department  
445 Hoes Lane  
Piscataway,  
NJ 08855-1331*

|                                   |                  |                                        |
|-----------------------------------|------------------|----------------------------------------|
| <i>IEEE Catalog Number</i>        | <i>99CH36282</i> | <i>ISBN 0-7803-5135-5 (softbound)</i>  |
| <i>Library of Congress Number</i> | <i>77-645125</i> | <i>ISBN 0-7803-5136-3 (casebound)</i>  |
| <i>ISSN:</i>                      | <i>0149-645X</i> | <i>ISBN 0-7803-5137-1 (microfiche)</i> |
|                                   |                  | <i>ISBN 0-7803-5138-X (CD-ROM)</i>     |

*'Kurt K. Wendt Library'  
University of Wisconsin-Madison  
215 N. Randall Avenue  
Madison, WI 53706-1688*

***IEEE MTT-S International Microwave Symposium***

*IEEE MTT-S International Microwave Symposium Digest 1977  
New York, Institute of Electrical and Electronics Engineers  
v. III. 28 cm. annual*

|                   |                                                                                |                       |
|-------------------|--------------------------------------------------------------------------------|-----------------------|
| <i>Continues:</i> | <i>IEEE MTT-S International Microwave Symposium Digest of Technical Papers</i> | <i>ISSN 0149-6298</i> |
| <i>Key title:</i> | <i>IEEE MTT-S International Microwave Symposium Digest</i>                     | <i>ISSN 0149-645X</i> |

- |                                                             |                                                                |
|-------------------------------------------------------------|----------------------------------------------------------------|
| <i>1. Microwaves-Congresses</i>                             | <i>2. Microwave Devices-Congresses</i>                         |
| <i>I. Institute of Electrical and Electronics Engineers</i> | <i>II. IEEE MTT-S International Microwave Symposium Digest</i> |

|                            |                  |                  |
|----------------------------|------------------|------------------|
| <i>TK7876.I184</i>         | <i>621.381'3</i> | <i>77-645125</i> |
| <i>Library of Congress</i> | <i>78</i>        | <i>MARC-S</i>    |

***Permission to Reprint or Copy***

*Abstracting is permitted with credit to the source. Libraries are permitted to photocopy beyond the limit of U.S. copyright law for private use of patrons those articles in this volume that carry a code at the bottom of the first page, provided the per-copy fee indicated in the code is paid through the Copyright Clearance Center; 222 Rosewood Drive, Danvers, MA 01923. For other copying, reprint, or republication permission, write to IEEE Copyrights Manager, IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331. All rights reserved.*

***Copyright © 1999 by The Institute of Electrical and Electronics Engineers, Inc.***

***PICTURES FOR FRONT COVERS***

***Volume 1: Front Cover:*** Malibu Coastline, © John Hinde Curteich, Inc.; ***Back Cover:*** top left, Redondo Beach, © John Hinde Curteich, Inc.; top right, Sail Boats, Newport Beach, © Anaheim Chamber of Commerce; middle, Laguna Beach, © John Hinde Curteich, Inc.; bottom left, Laguna Niguel, © Anaheim Chamber of Commerce; bottom right, Santa Monica, © John Hinde Curteich, Inc.; ***Background:*** Surf, © Anaheim Chamber of Commerce

***Volume 2: Front Cover:*** Laguna Beach, © Anaheim Chamber of Commerce; ***Back Cover:*** top, Los Angeles, © John Hinde Curteich, Inc.; middle left, Anaheim Convention Center, © Anaheim Chamber of Commerce; middle right, Hollywood Sign, © John Hinde Curteich, Inc.; bottom, Queen Mary, Long Beach, © Anaheim Chamber of Commerce; ***Background:*** Palm Trees, © Anaheim Chamber of Commerce  
***Volume 3: Front Cover:*** Santa Monica Pier, © John Hinde Curteich, Inc.; ***Back Cover:*** top left, California Palms, © John Hinde Curteich, Inc.; top right, San Juan Capistrano, © John Hinde Curteich, Inc.; middle left, California Poppies, © John Hinde Curteich, Inc.; bottom, Anacapa Island, © John Hinde Curteich, Inc.; ***Background:*** Santa Monica, © John Hinde Curteich, Inc.

***Volume 4: Front Cover:*** Griffith Park Observatory, Los Angeles, © PhotoDisc; ***Back Cover:*** top left, Satellite in Space, Courtesy of Hughes Space and Communications; top right, Galileo with Jupiter in background, Courtesy of NASA/JPL/Caltech; middle right, Voyager, Courtesy of NASA/JPL/Caltech; bottom right, Cassini, Courtesy of NASA/JPL/Caltech; bottom left, Satellite in Space, Courtesy of Hughes Space and Communications; ***Background:*** Composite of stars

Wend  
S  
IN5  
EL24  
PD  
V.1999  
1

30 4 924

# TABLE OF CONTENTS

## Volume 1

|                                                                           |        |
|---------------------------------------------------------------------------|--------|
| Table of Contents .....                                                   | iii    |
| Welcome from the 1999 Symposium General Chairman .....                    | vii    |
| 1999 Symposium Steering Committee .....                                   | xi     |
| Message from the 1999 Technical Program Chairs .....                      | xviii  |
| Technical Program Committee .....                                         | xix    |
| MTT-S Administrative Committee .....                                      | xxv    |
| Radio Frequency Integrated Circuits (RFIC) Symposium Committees .....     | xxvii  |
| Automatic RF Techniques Group Conference Steering Committee .....         | xxix   |
| 1999 Awards .....                                                         | xxx    |
| Future IEEE MTT-S International Microwave Symposia .....                  | xlvi   |
| Historical Exhibit .....                                                  | xlvi   |
| 1999 Microwave Symposium Technical Program schedule .....                 | xlxi   |
| Technical Sessions                                                        |        |
| MO1A Millimeter-Wave Oscillator Circuits .....                            | 3      |
| MO1D Modeling and Analysis of Generalized Networks .....                  | 25     |
| MO1E Surface and Leaky Waves on Printed Circuits .....                    | 51     |
| MO2A Microwave Oscillators .....                                          | 77     |
| MO2B Low Noise Components and Design Techniques .....                     | 99     |
| MO2C Millimeter-Wave Mixer and Multiplier Technology .....                | 121    |
| MO2D Neural and Distributed Models for Microwave Circuits .....           | 143    |
| MO2E Novel Field Techniques .....                                         | 165    |
| MO3A Microwave Digital Circuits .....                                     | 187    |
| MO3B Microwave Hybrid Technology .....                                    | 209    |
| MO3C Millimeter-Wave Amplifiers and Sources .....                         | 233    |
| MO3D Optimization and Neural Network Techniques .....                     | 255    |
| MO3E Focused Session: Commercial Microwave Sensor Technology .....        | 275    |
| MO4A Frequency Control Circuits .....                                     | 297    |
| MO4B Very High Power Components and Applications .....                    | 319    |
| MO4C HF/VHF/UHF Power Amplifiers .....                                    | 349    |
| MO4D Simulation Techniques for CAD .....                                  | 371    |
| MO4E Focused Session: Advances in Passive Remote Sensing .....            | 393    |
| Focused Sessions .....                                                    | III    |
| Sunday Workshops .....                                                    | V      |
| Panel and Rump Sessions .....                                             | VIII   |
| Friday Workshops .....                                                    | XII    |
| μAPS-Microwave Application and Product Seminars - Technical Program ..... | XV     |
| 1999 IEEE RFIC Symposium Schedule .....                                   | XVII   |
| Automatic RF Techniques Group Conference Schedule .....                   | XIX    |
| Author Index .....                                                        | XXIII  |
| Exhibition Guide .....                                                    | XXXIII |

# TABLE OF CONTENTS

## Volume 2

|                                                                                               |        |
|-----------------------------------------------------------------------------------------------|--------|
| Table of Contents .....                                                                       | iii    |
| 1999 International Microwave Symposium Technical Program Schedule .....                       | vii    |
| Technical Sessions .....                                                                      | 411    |
| TU1A Nonlinear MOS and HBT Modeling .....                                                     | 413    |
| TU1B High Density Subsystem Packaging Technologies .....                                      | 439    |
| TU1D Millimeter-Wave Applications .....                                                       | 461    |
| TU1E Joint RFIC and IMS Session: Low Noise MMICs .....                                        | 483    |
| TU2A Plenary Session: Technologies for the New Millenium .....                                | 505    |
| TU3A Large-Signal FET Modeling for Power Amplifier and Mixer Design .....                     | 511    |
| TU3B Spatial Power Combining .....                                                            | 537    |
| TU3C Si Technologies for RF Millimeter-Wave Applications .....                                | 567    |
| TU3D Biological Effects and Medical Applications .....                                        | 589    |
| TU3E Focused Session: Terabit Technologies for the 21 <sup>st</sup> Century .....             | 611    |
| TU4A Interconnects and Transitions .....                                                      | 623    |
| TU4B Phased Array and Active Antennas .....                                                   | 645    |
| TU4C GaAs Technology and Applications .....                                                   | 675    |
| TUF1 Interactive Forum: CAD Algorithms, Techniques and Models .....                           | 697    |
| TUF2 Interactive Forum: Non-Linear Circuits and Modeling Techniques .....                     | 723    |
| TUF3 Interactive Forum: Amplifiers and Active Components .....                                | 757    |
| TUF4 Interactive Forum (Joint with RFIC): Monolithic Mixers for Commercial Applications ..... | 839    |
| TUF5 Interactive Forum: Student Papers Final Selection .....                                  | 849    |
| Focused Sessions .....                                                                        | III    |
| Sunday Workshops .....                                                                        | V      |
| Panel and Rump Sessions .....                                                                 | VIII   |
| Friday Workshops .....                                                                        | XII    |
| μAPS-Microwave Application and Product Seminars - Technical Program .....                     | XV     |
| 1999 IEEE RFIC Symposium Schedule .....                                                       | XVII   |
| Automatic RF Techniques Group Conference Schedule .....                                       | XIX    |
| Author Index .....                                                                            | XXIII  |
| Exhibition Guide .....                                                                        | XXXIII |

# TABLE OF CONTENTS

## Volume 3

|                                                                                      |        |
|--------------------------------------------------------------------------------------|--------|
| Table of Contents .....                                                              | iii    |
| 1999 International Microwave Symposium Technical Program Schedule .....              | vii    |
| Technical Sessions .....                                                             | 851    |
| WE1A Passive Structures .....                                                        | 853    |
| WE1B Focused Session: Optical Processing of Microwave Signals .....                  | 875    |
| WE1C Filters-Network Theory .....                                                    | 897    |
| WE1D Focused Session: Submillimeter-Wave and Terahertz Technologies .....            | 923    |
| WE1E High Power Transistor Amplifiers for X-Band Through Ka-Band .....               | 945    |
| WE2A Advances in Nonlinear Design and Simulation Techniques .....                    | 975    |
| WE2B Microwave Photonic Components .....                                             | 997    |
| WE2C Filters with Novel Resonator Structures .....                                   | 1019   |
| WE2D Microwave Communication Systems for Y2K and Beyond .....                        | 1045   |
| WE2E Focused Session: Processing Technologies for the 21 <sup>st</sup> Century ..... | 1067   |
| WE3A Power Amplifier Devices and Technology for Wireless Applications .....          | 1085   |
| WE3B Optically Controlled Array Antennas .....                                       | 1107   |
| WE3C Planar and Coaxial Filters .....                                                | 1125   |
| WE3D Ferrite Devices and Characterization .....                                      | 1151   |
| WE3E Southern California Firsts in Microwave Systems .....                           | 1175   |
| WE4A Device Technology for Power Amplifiers .....                                    | 1181   |
| WE4B Fiber Fed Wireless Access Systems .....                                         | 1199   |
| WE4C Active and MEMS Filters .....                                                   | 1221   |
| WEF1 Interactive Forum: Analysis, Techniques and Application of EM Theory .....      | 1243   |
| WEF2 Interactive Forum: Passive Components and Filters .....                         | 1309   |
| WEF3 Interactive Forum: Ferrite Devices and Characterization .....                   | 1359   |
| Focused Sessions .....                                                               | III    |
| Sunday Workshops .....                                                               | V      |
| Panel and Rump Sessions .....                                                        | VIII   |
| Friday Workshops .....                                                               | XII    |
| μAPS-Microwave Application and Product Seminars - Technical Program .....            | XV     |
| 1999 IEEE RFIC Symposium Schedule .....                                              | XVII   |
| Automatic RF Techniques Group Conference Schedule .....                              | XIX    |
| Author Index .....                                                                   | XXIII  |
| Exhibition Guide .....                                                               | XXXIII |

# TABLE OF CONTENTS

## Volume 4

|                                                                                         |        |
|-----------------------------------------------------------------------------------------|--------|
| Table of Contents .....                                                                 | iii    |
| 1999 Microwave Symposium Technical Program Schedule .....                               | vii    |
| Technical Sessions .....                                                                | 1389   |
| TH1A Integrated Systems for Wireless .....                                              | 1391   |
| TH1B Novel Transition Structures .....                                                  | 1417   |
| TH1D Microwave Acoustic Applications .....                                              | 1439   |
| TH1E New Techniques in Time Domain Modeling .....                                       | 1457   |
| TH2A Intelligent Transportation Systems .....                                           | 1483   |
| TH2B Micromachined Components .....                                                     | 1505   |
| TH2C Focused Session: Microwave Applications of Photonic Bandgap Materials .....        | 1527   |
| TH2D Superconducting Components and Subsystems .....                                    | 1541   |
| TH2E Advances in Time Domain EM Field Analysis .....                                    | 1567   |
| TH3A Sensor Applications .....                                                          | 1593   |
| TH3B Passive Circuit Elements and Components .....                                      | 1615   |
| TH3C Microwave Measurement Techniques .....                                             | 1633   |
| TH3D Frequency Domain Numerical Techniques I .....                                      | 1663   |
| TH4A Frequency Domain Numerical Techniques II .....                                     | 1689   |
| TH4B Couplers and Baluns .....                                                          | 1715   |
| TH4C Joint ARFTG and IMS Session: Automated Characterization Techniques .....           | 1741   |
| THF1 Interactive Forum: Technologies at the Edge of the Microwave Frequency Range ..... | 1767   |
| THF2 Interactive Forum: Biological Effects .....                                        | 1813   |
| THF3 Interactive Forum: Active and Passive Phased Array Systems .....                   | 1823   |
| THF4 Interactive Forum: RF Wireless and Sensors .....                                   | 1837   |
| THF5 Interactive Forum: RF Component Measurement and Characterization Techniques .....  | 1875   |
| Late papers .....                                                                       | 1913   |
| Focused Sessions .....                                                                  | III    |
| Sunday Workshops .....                                                                  | V      |
| Panel and Rump Sessions .....                                                           | VIII   |
| Friday Workshops .....                                                                  | XII    |
| μAPS-Microwave Application and Product Seminars - Technical Program .....               | XV     |
| 1999 IEEE RFIC Symposium Schedule .....                                                 | XVII   |
| Automatic RF Techniques Group Conference Schedule .....                                 | XIX    |
| Author Index .....                                                                      | XXIII  |
| Exhibition Guide .....                                                                  | XXXIII |

# MODELING AND ANALYSIS OF MULTILEVEL SPIRAL INDUCTORS FOR RFICS

R. D. Lutz, Y. Hahm, A. Weisshaar, V. K. Tripathi  
Electrical and Computer Engineering Department  
Oregon State University  
Corvallis, Oregon 97331

and

H. Wu, HP EEsof, Santa Rosa, CA 95403  
N. Kanaglekar, HP EEsof, Westlake Village, CA 91362

**Abstract**—An accurate CAD-oriented modeling methodology for multilevel rectangular spiral inductors with enhanced inductance and/or quality factor is presented. The method is based on a distributed equivalent circuit model whose elements are computed using Spectral Domain and Partial Element Equivalent Circuit (PEEC) techniques. Examples of typical two layer spirals in Bi-CMOS and CMOS technologies are presented to illustrate the accuracy of the model as well as the enhanced performance of the multilevel structures.

## I. Introduction

Multilevel spiral inductors have been used to enhance the quality factor and inductance/area ratios of spiral inductors in silicon based RFICs and GaAs MMICs [1], [2]. Enhanced  $Q$  multilevel spirals generally consist of identical spirals placed on multiple metallization layers and shunted together by vias. Enhanced inductance can be achieved by judiciously placing multiple spirals on different metallization layers in a series configuration in order to increase the mutual inductive coupling. Even though a number of experimental results have been reported, accurate models and modeling methodologies incorporating all of the conductor and substrate losses and inductive and capacitive coupling are not available.

In this paper a complete modeling methodology for multilevel spirals on a lossy substrate is presented. An example multilevel spiral (MLS) structure is illustrated in Figure 1. This particular configuration consists of two series-connected spirals and may be viewed as a top level coil which spirals inward placed directly on top of an identical coil on the lower level which spirals outward in the same sense. The modeling methodology presented in this paper takes into account all significant coupling effects between the different segments of the spiral as well as the lossy substrate. In particular, our model takes into account the substrate skin effect which leads to higher losses and reduced inductance,

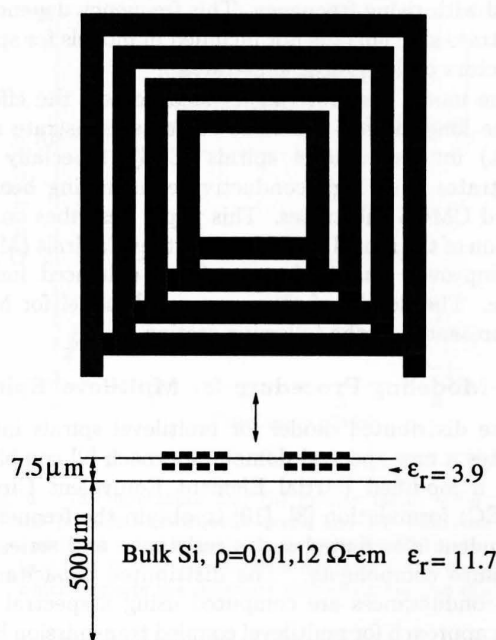


Fig. 1. Example of a two level series-connected spiral inductor on lossy silicon substrate.

especially for heavily doped CMOS substrates.

## II. Modeling Spiral Inductors on Lossy Substrates

The modeling methodologies for planar spiral inductors on low-loss substrates are well known, and models typically consist of lumped element equivalent circuits [3]. In general, such lumped element circuits involve very simple topologies which can accurately model the characteristics of a spiral on a low-loss substrate. Similarly, equivalent circuit models for spiral inductors in silicon (Si-SiO<sub>2</sub>) technology have been developed for

moderately doped substrates (e.g.  $\rho = 10 \text{ } \Omega\text{-cm}$ ) [4], [5]. Here, substrate losses are typically modeled in the equivalent circuit in terms of a shunt conductance to represent the silicon substrate and associated transverse (shunt) currents. This proves to be sufficiently accurate for substrate conductivities on the order of  $10 \text{ S/m}$  or lower ( $\rho \approx 10 \text{ } \Omega\text{-cm}$  or higher), and frequencies in the low Gigahertz range. However, for higher substrate conductivities such as in CMOS technology, the skin depth,  $\delta = 1/\sqrt{\pi\mu\sigma f}$ , of the semiconducting substrate can become sufficiently small (e.g. on the order of the substrate thickness), such that longitudinal substrate currents can be significant [6], [7]. Due to their proximity to the spiral inductor, the longitudinal substrate currents can lead to a significant reduction in inductance and increase in series resistance of the spiral with rising frequency. This frequency dependent substrate skin effect is not included in models for spiral inductors on lower loss substrates.

The model described in [8] incorporates the effects of the longitudinal substrate currents (substrate skin effect) for single level spirals (SLS), especially for substrates with high conductivities including heavily doped CMOS substrates. This paper describes an extension of the model for SLS to multilevel spirals (MLS) for improved quality factor and/or enhanced inductance. The details of this augmented model for MLS are presented in the following section.

### III. Modeling Procedure for Multilevel Spirals

The distributed model for multilevel spirals incorporates a new spectral domain approach [9] combined with a modified Partial Element Equivalent Circuit (PEEC) formulation [8], [10] to obtain the frequency-dependent distributed series resistance and series inductance components. The distributed capacitances and conductances are computed using a spectral domain approach for multilevel coupled transmission lines on a multi-layered substrate. Each leg or segment of the spiral is modeled in terms of a lumped element equivalent circuit which is appropriately coupled both capacitively and inductively to all other elements of the circuit for which the coupling terms are significantly large. Figure 2 illustrates the relationship between the model elements and the physical structure. The shunt elements utilize the common C-G-C topology. The frequency dependent response of the C-G-C model is in good agreement with values computed from the spectral domain approach over a wide frequency range. The frequency-dependent self and mutual series resistances and self and mutual partial inductances incorporate the effects of longitudinal substrate currents, as well as the skin effect in the metallizations.

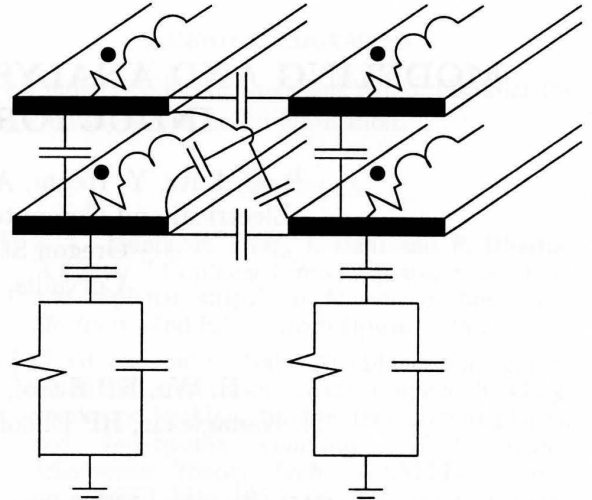


Fig. 2. Equivalent circuit modeling of multilevel structure.

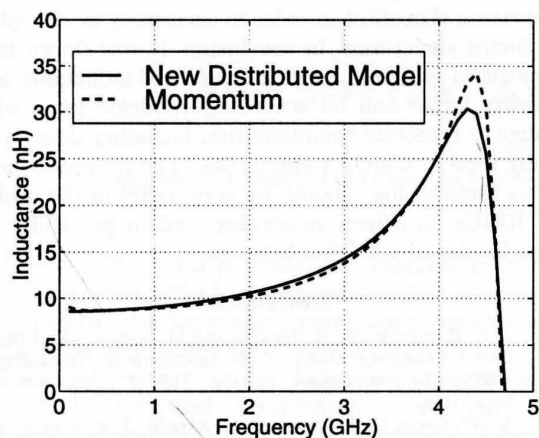
### IV. Simulation Results and Discussion

The new modeling approach described above has been applied to both series-connected and parallel-connected two-level spiral inductors on silicon substrates with medium and high conductivities.

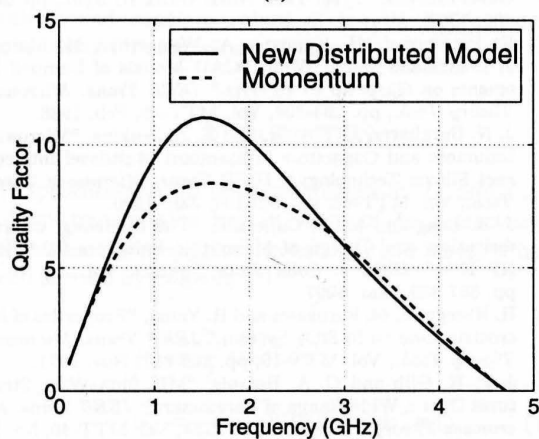
#### A. Series-Connected Spirals

Figures 3 and 4 show the inductance and quality factor ( $Q = \omega L_{eff}/Re[Z_{in}]$ ) as functions of frequency for a four turn, two level series-connected spiral over a typical BiCMOS substrate with  $\rho = 12 \text{ } \Omega\text{-cm}$ , as well as for a CMOS substrate with  $\rho = 0.01 \text{ } \Omega\text{-cm}$ , as illustrated in Figure 1. In both cases, the lower spiral is located  $4.5 \text{ } \mu\text{m}$  above the silicon substrate. The dimensions of both spirals are  $w = s = 13 \text{ } \mu\text{m}$  and area =  $226 \times 226 \text{ } \mu\text{m}^2$ . The inductance and quality factor were computed using the distributed model described in this paper and compared with full wave results obtained from HP Momentum. In addition, the case with the CMOS substrate includes the results obtained from a distributed model that only accounts for the shunt substrate currents in order to exemplify the need for inclusion of the substrate skin effect for spiral inductors on substrates with high conductivity.

It is evident that the inductance enhancement from the two level series configuration, which in this case is an increase in base inductance from  $\sim 2.3 \text{ nH}$  to  $\sim 8.8 \text{ nH}$ , comes at the expense of a lower self resonant frequency. However, for a given inductance value, the series resistance of the multilevel series configuration will be reduced, which can be advantageous. Also, in a lossy environment such as in BiCMOS and CMOS tech-

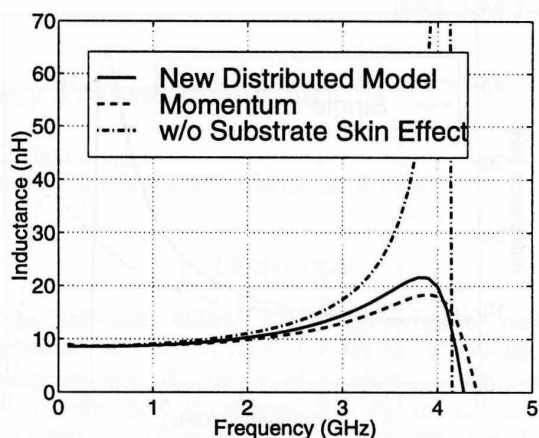


(a)

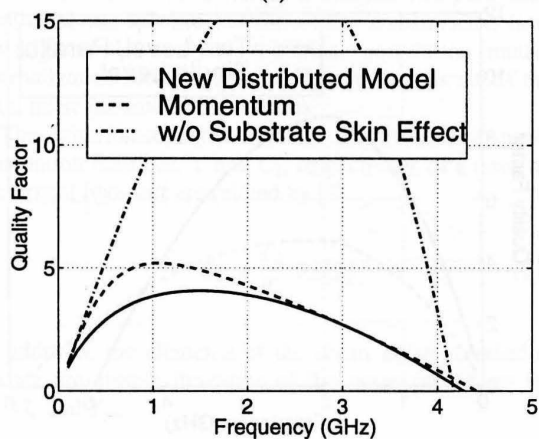


(b)

Fig. 3. (a) inductance and (b) quality factor obtained with the proposed distributed model and HP Momentum for a multilevel spiral inductor in a typical BiCMOS environment ( $\rho = 12 \Omega\text{-cm}$ ).



(a)



(b)

Fig. 4. (a) inductance and (b) quality factor obtained with the proposed distributed model and HP Momentum for a multilevel spiral inductor in a typical CMOS environment ( $\rho = 0.01 \Omega\text{-cm}$ ). Results obtained with a distributed model which neglects the substrate skin effect are also shown.

nologies, the multilevel structures can often achieve a higher quality factor in the low frequency range than their single level counterparts, as previously noted in [1].

### B. Parallel-Connected Spirals

Figure 5 shows the simulated inductance and quality factor for two eight turn spiral inductors on a typical CMOS substrate ( $\rho = 0.01 \Omega\text{-cm}$ ). One of the spirals exists only on the upper metallization layer (SLS), and the other structure uses two metallization layers in parallel and shunted together by vias (MLS). The total area of both structures is  $226 \times 226 \mu\text{m}^2$ . The width and spacing for both spiral inductor structures are  $6 \mu\text{m}$ , and the heights above the silicon substrate for

the two metallization layers are  $4.5 \mu\text{m}$  and  $7.5 \mu\text{m}$ , respectively. The via connections are taken to be at each corner and are assumed to be perfectly conducting.

As expected, the quality factor achieved with the shunted two-level structure is greater than that of the single level counterpart. However, the self-resonant frequency of the parallel-connected spiral is slightly lower, mainly due to the increased shunt oxide capacitance which results from the lower level being closer to the substrate. The low frequency inductance values for both structures are virtually identical, indicating that inductance is lowered only slightly by the parallel connection.

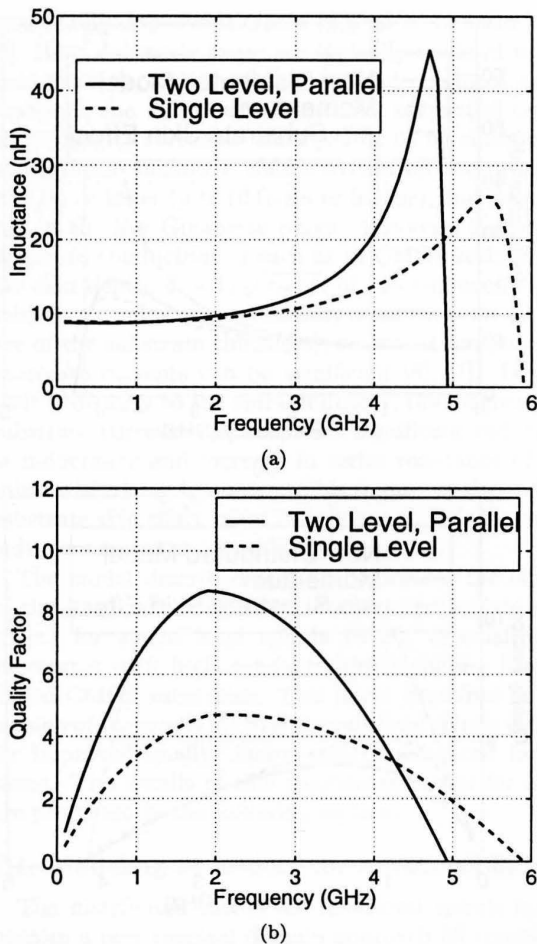


Fig. 5. Comparison of (a) inductance and (b) quality factor for a two level parallel-connected spiral inductor and a single level spiral in a typical CMOS environment ( $\rho = 0.01 \Omega\text{-cm}$ ). All results are computed using distributed equivalent circuit models including the substrate skin effect.

## V. Conclusion

A new modeling methodology for multilevel spiral inductors on lossy substrates has been presented. It has been shown that the multilevel series configuration yields a higher inductance/area ratio as well as higher quality factors for low frequencies, although the usable frequency range is reduced as compared to a single level spiral with the same inductance value. Parallel-connected multilevel spiral inductors yield a lower series resistance and can often achieve a higher quality factor than the identical single level structure. This, however, comes at the expense of a slightly reduced self resonant frequency. It was shown that in a high conductivity environment, it is necessary to account for the

substrate skin effect in order to accurately model spiral inductor structures. In conclusion, it was shown that multilevel spiral inductors for enhanced inductance and quality factor can be accurately modeled for a wide range of substrate conductivities, including those typically used in CMOS technologies. The proposed modeling methodology should be very useful in the design of RFICs on silicon substrates, and in particular on heavily-doped CMOS substrates.

## References

- [1] J. N. Burghartz, K. A. Jenkins and M. Soyuer, "Multilevel-Spiral Inductors Using VLSI Interconnect Technology," *IEEE Electron Device Letters*, Vol. 17, pp. 428-430, Sept. 1996.
- [2] M. W. Geen, G. J. Green, R. G. Arnold, J. A. Jenkins and R. H. Jansen, "Miniature Multilayer Spiral Inductors for GaAs MMICs," *Proc. 1989 IEEE GaAs IC Sym.*, pp. 303-306, 1989.
- [3] E. Pettenpaul, H. Kapusta, A. Weisgerber, H. Mampe, J. Luginsland and I. Wolff, "CAD Models of Lumped Elements on GaAs up to 18 GHz," *IEEE Trans. Microwave Theory Tech.*, pp. 294-304, Vol. MTT-36, Feb. 1988.
- [4] J. N. Burghartz, M. Soyuer, and K. A. Jenkins, "Microwave Inductors and Capacitors in Standard Multilevel Interconnect Silicon Technology," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-44, pp. 100-104, Jan. 1996.
- [5] J. R. Long and M. A. Copeland, "The Modeling, Characterization, and Design of Monolithic Inductors for Silicon RF IC's," *IEEE J. Solid State Circuits*, Vol. 32, No. 3, pp. 357-369, Mar. 1997.
- [6] H. Hasegawa, M. Furukawa and H. Yanai, "Properties of Microstrip Line on Si-SiO<sub>2</sub> System," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-19, pp. 869-881, Nov. 1971.
- [7] J. P. K. Gilb and C. A. Balanis, "MIS Slow-Wave Structures Over a Wide Range of Parameters," *IEEE Trans. Microwave Theory Tech.*, pp. 2148-2154, Vol. MTT-40, No. 12, Dec. 1992.
- [8] R. D. Lutz, Y. Hahm, A. Weisshaar, V. K. Tripathi, A. Grzegorek, W. McFarland and J. Meyer, "Modeling of Spiral Inductors on Lossy Substrates for RFIC Applications," *IEEE 1998 MTT-S Sym. Digest*, Baltimore, MD, pp. 1855-1858, June 1998.
- [9] A. Tripathi, Y. Hahm, A. Weisshaar and V. K. Tripathi, "Quasi-TEM spectral domain approach for calculating distributed inductance and resistance of microstrip on Si-SiO<sub>2</sub> substrate," *IEEE Electronics Letters*, pp. 1330-1331, Vol. 34, No. 13, June 1998.
- [10] A. E. Ruehli, "Equivalent Circuit Models for Three-Dimensional Multiconductor Systems" *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-22, pp. 216-221, Mar. 1974.