Theoretical and Experimental Study of Microstrip Discontinuities in Millimeter Wave Integrated Circuits

FINAL REPORT

Submitted to Army Research Office

by

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1 Final Report

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- **Title of Proposal:**

  Theoretical and Experimental Study of Microstrip Discontinuities in Millimeter Wave Integrated Circuits.

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- **Authors of the Report:** Linda P.B. Katehi

- **List of Interim Reports and Manuscripts Submitted or Published Under Full or Partial NSF Sponsorship During this Reporting Period:**

  1. L.P. Dunleavy, P.B. Katehi, "A New Method For Discontinuity Analysis in Shielded Microstrip," *1988 IEEE MTT-S International Microwave Symposium Digest*,New York, NY, pp. 701-704.
  2. L.P. Dunleavy, P.B. Katehi, "A Generalized Method for Analyzing Shielded

Thin Microstrip Discontinuities," *IEEE Transactions on Microwave Theory and Techniques*, vol.36, No.12, Dec.1988, pp. 1758-1766.

3. L.P. Dunleavy and P.B. Katehi, "Shielding Effects in Microstrip Discontinuities," *IEEE Transactions of Microwave Theory and Techniques*, vol.36, No.12, Dec.1988, pp.1767-1774.
4. M.E. Coluzzi, P.B. Katehi, "Theoretical Characterization of an Air-Bridge," *Technical Report ARO-024562-1-T*, EECS Department, University of Michigan, Ann Arbor, June 1988.
5. T.G. Livernois, P.B. Katehi, "Via-Slot Coupling of Shielded Microstrip Lines," *Technical Report ARO-024562-2-T*, EECS Department, University of Michigan, Ann Arbor, April 1988.
6. T.E. van Deventer, P.B. Katehi, "Computer Program for Mode Search in Partially Filled Waveguides," *Technical Report ARO-024562-3-T*, EECS Department, The University of Michigan, Ann Arbor, June 1988.
7. T.E. van Deventer, P.B. Katehi and A.C. Cangellaris, "High Frequency Conductor and Dielectric Losses in Shielded Microstrip," *1989 IEEE MTT-S International Microwave Symposium Digest*, Long Beach, CA, pp. 919-922.
8. W.P. Harokopus, P.B. Katehi, "Analysis of Multilayer Irregular Microstrip Discontinuities Including Radiation Losses," *Proceedings of the 19th European Microwave Conference*, London, England, pp. 745-750.
9. W.P. Harokopus, P.B. Katehi, "Characterization of Microstrip Disconti-

nuities on Multilayer Dielectric Substrates Including Radiation Losses," *IEEE Transactions on Microwave Theory and Techniques*, vol.37, No.12, Dec. 1989, pp. 2058-2066.

10. T.E. van Deventer, P.B. Katehi and A.C. Cangellaris, "An Integral Equation Method for the Evaluation of Conductor and Dielectric Losses in High-Frequency Interconnects," *IEEE Transactions on Microwave Theory and Techniques*, vol. 7, No.12, pp. 1964-1972.
11. W.P. Harokopus, P.B. Katehi, "Electromagnetic Coupling and Radiation Loss Considerations in Microstrip MMIC Design," submitted for publication in the *IEEE Transactions on Microwave Theory and Techniques.*
12. T.E. van Deventer, P.B. Katehi, J.Y. Josefowicz and D.B. Rensch, "High Frequency Characterization of High-Temperature Superconducting Thin Film Lines," *1990 IEEE MTT-S International Microwave Symposium Digest*, Dallas, Texas, pp. 285-288.
13. T.E. van Deventer, P.B. Katehi, J.Y. Josefowicz and D.B. Rensch, "High Frequency Characterization of High-Temperature Superconducting Thin Film Lines," submitted for publication in the *IEEE Trans. of Microwave Theory and Techniques.*

- **Scientific Personnel Supported by this Project:**
  - *Faculty:*

    Linda P.B. Katehi

Dimitris Pavlidis

- *Graduate Students:*

W.P. Harokopus

T.E. van Deventer

M.E. Coluzzi

M. Weiss

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2 Statement of the Problem Studied

This effort has addressed the general problem of developing more accurate analytical methods to characterize open and shielded microstrip structures as used in millimeter-wave integrated circuits. Emphasis was placed on the open structures since past theoretical treatment of this problem is considered inadequate, particularly with regard to radiation losses. Consideration was also given to the shielded case which is more common in practical circuit design.

3 List of Research Tasks

Title	Personnel Involved with the Research
Theoretical Characterization of an Air-Bridge	Linda P.B. Katehi Mike E. Coluzzi
High Frequency Conductor Losses in Microstrip Interconnects	Linda P.B. Katehi T. Emilie van Deventer
Shielding Effects on the Phase Velocity of Microstrip Lines	Linda P.B. Katehi Larry P. Dunleavy
Theoretical Characterization of Open Microstrip Discontinuities	Linda P.B. Katehi William P. Harokopus
Gate Capacitance Modeling of GaAs MESFETs in Millimeter Wave Frequencies	Linda P.B. Katehi Dimitris Pavlidis Matthias Weiss
High Frequency Characterization of Superconducting Lines	Linda P.B. Katehi T. Emilie van Deventer

4 Summary of the Most Important Results

4.1 Theoretical Characterization of Open Microstrip Discontinuities

During the reported period a fullwave method has been successfully implemented to a wide variety of microstrip discontinuities and components. The applied analysis accounts for electromagnetic coupling, radiation, and substrate effects, and has shown excellent accuracy in the high-frequency characterization of a variety of microstrip structures. Although not a substitute for less intensive approximate techniques, this method has proven to be versatile for microstrip characterization in regions where these techniques fail. The aim of our work was to characterize commonly used microstrip elements in an effort to establish useful design guidelines.

Using the method discussed above, a microstrip meander line was extensively studied. Results were derived which demonstrated the effect of coupling on the slow-wave nature of the line, and quantified return loss, radiation and conductor loss for a phase shifting section. Also a meander line having a pencil beam has been shown.

Another type of microstrip circuits considered were transmission line junctions and stubs. Scattering parameters and radiation losses were evaluated for right-angle and mitered bends, multiport tee and cross junctions. Several stub geometries were considered and their bandwidth and radiation losses were evaluated. Furthermore, a matching circuit for a 94 GHz oscillator was examined to illustrate the effect of spurious coupling and radiation.

4.2 High Frequency Characterization of High T_c Superconducting Lines

A major advantage of high critical temperature superconductors is the reduced surface resistance of the lines as compared to the normally conducting metal strips. These lines are made of thin films with a thickness large compared to the penetration depth of the magnetic field in the superconductor.

Several groups have reported theoretical results for the surface resistance and propagation constant of high T_c films and strips. One common characteristic in all these attempts has been the discrepancies between theoretical and experimental results which in the case of attenuation constant may be of a few orders of magnitude. This disagreement is mainly due to the inadequacy of the implemented theoretical models to characterize the electromagnetic behavior of the high T_c superconducting materials as they are presently made.

To avoid the shortcomings of the existing theoretical treatments, we developed a method which does not attempt to solve for the electromagnetic fields inside the superconducting thin films. Only the electric/magnetic field relation on the surface of the strips is utilized to create an equivalent surface impedance boundary which replaces the superconducting strips. Due to the fact that the superconducting strips made today have a very large width-to-thickness ratio, the electric/magnetic field ratio on the strip surface is almost identical to the surface impedance of a thin superconducting plane. For this reason, measured values of this surface impedance were used to simulate the superconducting strip very accurately.

This approach was used to determine the temperature and frequency-dependent losses in superconducting lines with arbitrary parameters and evaluate propagation constant and characteristic impedance as functions of the geometry.

4.3 High Frequency Conductor Losses in Microstrip Interconnects

Shielded microstrip lines are widely used in microwave integrated circuits where they perform a great variety of functions. It is therefore very important to have an accurate knowledge of their characteristics, i.e. phase velocity, characteristic impedance and losses as a function of geometry and frequency. Because dissipative losses impose a major limitation on the performance of microstrip interconnects, passive circuits and radiating elements, it is of interest to improve loss analysis, whereby effects of substrate and non-perfectly conducting strips can be treated individually. Ohmic losses due to the finite conductivity of the strips is the prevalent loss effect at microwave and millimeter wave frequencies, and have been studied by several authors during the past fifty years but have been limited to lower frequencies and electrically thick strips.

During the reported period, an integral equation method has been developed to solve for the complex propagation constant in multi-layered planar structures with arbitrary number of strip conductors on different levels. The Green's function included in the integral equation has been derived by using a generalized impedance boundary formulation. The microstrip ohmic losses have been evaluated by using an equivalent frequency-dependent impedance surface which is derived by solving for the fields inside the conductors. This impedance surface replaces the conducting strips and takes into account the thickness and skin effect of the strips at high frequencies.

Using the above described procedure, results have been generated for single microstrip lines on one and two-level multiple interconnects. Also, the effects of various parameters such as frequency, thickness of the lines and substrate surface roughness on the complex propagation constant are investigated. Results derived from this analysis show very good agreement with data available in the literature.

4.4 Shielding Effects on the Phase Velocity of Microstrip Lines

An integral equation method has been developed for the accurate evaluation of shielding effects on the propagation properties of shielded microstrip lines. The integral equation has been derived by applying reciprocity theorem and then solved by the method of moments. Numerical results have been derived and compared to experimental ones for verification of the theory.