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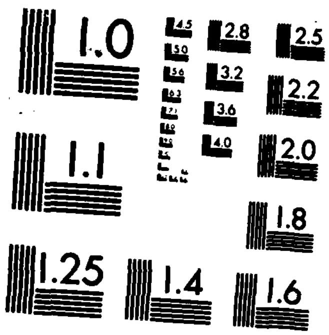


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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the final report for research performed under DAAG 29-83-K-0067. The research performed during the duration of this grant has made an impact in the areas of: (a) Substrate-superstrate effects on printed circuit antennas (b) Modeling electromagnetically coupled microstrip dipoles in a substrate-superstrate configuration (c) Modeling Microstrip Discontinuities and (d) Investigating substrate anisotropy effects on a variety of integrated circuit structures. During the period of research, very sophisticated algorithms were developed on Green's function methods and integral equation solutions based on a variety of numerical procedures.

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FINAL REPORT - CONTRACT NO. DAAG 29-83-K-0067

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## ABSTRACT

This is the final report for research performed under Contract No. DAAG 29-83-K-0067. The research performed during the duration of this grant has made an impact in the areas of: (a) Substrate-superstrate effects on printed circuit antennas (b) Modeling electromagnetically coupled microstrip dipoles in a substrate-superstrate configuration (c) Modeling Microstrip Discontinuities and (d) Investigating substrate anisotropy effects on a variety of integrated circuit structures. During the period of research, very sophisticated algorithms were developed on Green's function methods and integral equation solutions based on a variety of numerical procedures.

## SUMMARY OF RESEARCH

Printed circuit antennas consisting of a planar radiating element on a single substrate layer are attractive components both at microwave and millimeter wave frequencies because of the advantages they possess, such as low weight, conformability, polarization diversity, and low cost. They have been analyzed fairly extensively in the past, and their properties and limitations are well known [1]-[5]. Their limitations include low efficiency and/or low radiation resistance, no radiation at the horizon, limited flexibility in pattern shape, low gain, and narrow bandwidth. One method of improving printed antenna performance is by using the antenna element in a substrate-superstrate geometry, shown in figure 1, which consists of a grounded substrate layer with a superstrate (cover) layer on top. This research will address fundamental ways by which a superstrate layer can affect, and improve, performance of a printed circuit antenna.

In order to examine the fundamental effects that a superstrate has on printed antenna performance, the problem of a Hertzian (infinitesimal) dipole in a substrate-superstrate geometry will first be solved, which is equivalent to finding the Green's function. In the far-field the

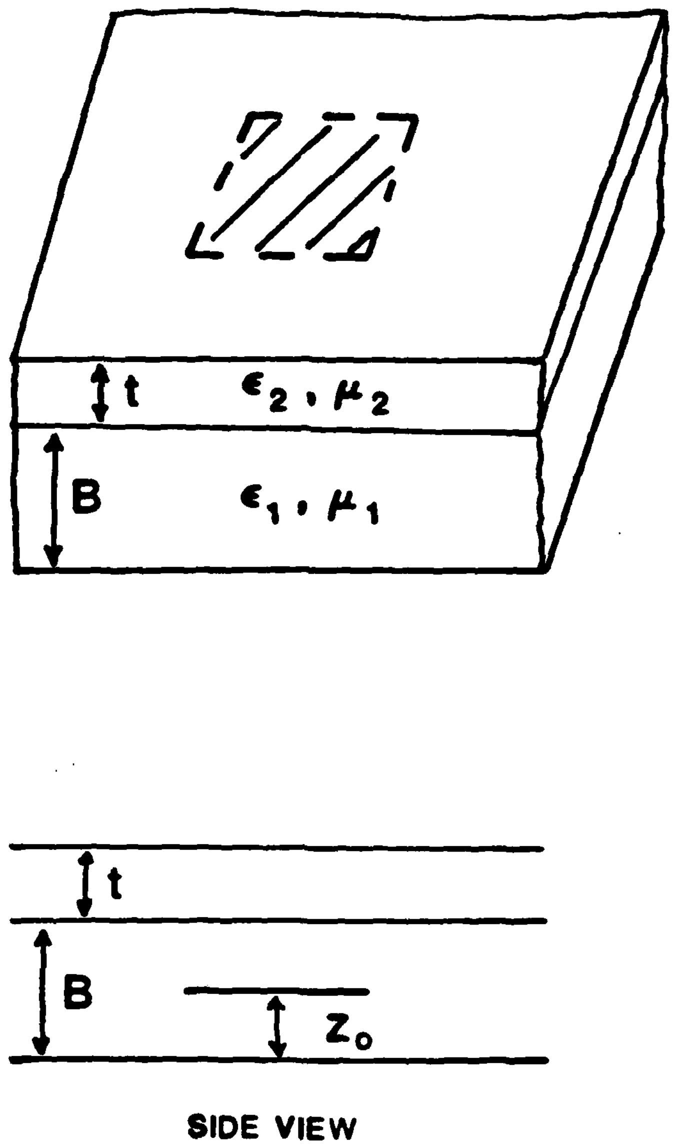



Fig. 1. Printed antenna in a substrate-superstrate geometry.

radiation and surface wave fields from an arbitrary planar current source differ from this Hertzian dipole solution only by appropriate shape-factor terms to account for the specific shape of the radiating element. Hence all of the basic superstrate effects on printed antenna radiation performance can be seen from an analysis of the Hertzian dipole case.

### 1. Fundamental Superstrate Effects on Printed Circuit Antennas

From the analysis of the Hertzian dipole case, a superstrate layer may be seen to affect printed antenna performance in several interesting ways. A brief description of some of the ways in which a superstrate layer can affect and improve performance is given below.

#### Optimization of Efficiency

For a dipole on a single substrate layer, it is often difficult to achieve a satisfactory radiation efficiency without sacrificing performance in one or more other areas. This is because the efficiency decreases in general for either increasing substrate thickness or substrate dielectric constant. Hence, in order to obtain high efficiencies, it is necessary to either use materials which have low dielectric constants, or else keep the substrate layer very thin. For integrated circuit applications it is often desired to use materials such as GaAs which have high dielectric constants. For the single layer case the efficiency can then be kept high only by using a very thin substrate. However, for substrates which are electrically thin the radiated power of the dipole will be very small, since the radiation resistance increases with substrate thickness. Hence a tradeoff exists between efficiency and radiated power with respect to substrate thickness for a given substrate material. Furthermore, studies have shown [20] that the bandwidth of full-length dipoles and patches increases with increasing substrate thickness and dielectric constant, so that a trade-off exists between efficiency and bandwidth. For materials such as GaAs, the trade-off between efficiency and either radiated power or bandwidth may result in unsatisfactory performance. However, by using a superstrate with a higher index of refraction than the substrate, a significant improvement in efficiency can be obtained. In fact, by properly using a superstrate layer, it will be seen possible to achieve an elimination of all surface waves, resulting in an efficiency (due to surface-wave effects) of 100%.

Radiation Into the Horizon

Another limitation characteristic of antenna elements above a ground plane, such as printed antennas, is that the far-field radiation always tends to zero, in general, at the "horizon", or as $\theta \to \pi/2$. A phenomenon called radiation into the horizon will be discussed however, in which the far-field radiation of a printed antenna extends down to a nonzero value as $\theta \to \pi/2$. An analytical discussion of this phenomenon will be given, and a ray optics interpretation will be presented to aid in its physical understanding. Based on this phenomenon criteria will then be given for radiation patterns which are nearly omnidirectional, in either the $\overline{E}$- or $\overline{H}$-plane. An extension of this method which allows for a limited degree of pattern shaping will also be discussed.

Gain Enhancement

Another way in which a superstate layer can be used to improve printed antenna performance is in the increase of gain. A method of using a superstrate layer to significantly improve the gain of a printed antenna, referred to as the resonance gain method, will be discussed. By properly choosing the layer thicknesses and dipole position, very large gains may be realized at any desired angle $\theta$ with this method, when a superstrate having either $\epsilon >> 1$ or $\mu >> 1$ is used. The gain varies proportionally to either the $\epsilon$ or $\mu$ of the superstrate in this method depending on the configuration. However, the bandwidth is seen to vary inversely to the gain, so that a reasonable gain limit is actually established for practical antenna operation. Asymptotic formulas for resonance gain, beamwidth, and bandwidth will be derived, which show explicitly the behavior of the resonance gain phenomenon. The resonance gain method will also be seen to combine with the phenomenon of radiation into the horizon, resulting in high gain patterns which are scanned to the horizon. An extension of the resonance gain method for producing patterns having resonance gain at two different angles will also be discussed.

## 2. Analysis of Planar Strip Geometries

After the fundamental effects of a superstrate layer on the Hertzian dipole have been discussed, several different classes of full-length planar strip geometries, shown in figure 2, will be considered. These include the microstrip transmission line, the center-fed strip dipole, the mutual impedance between two strip dipoles, and the excitation of a strip dipole by transmission line coupling. For all of these planar structures a convenient approach to use is the plane-wave spectrum method, which eliminates the need to perform numerical spatial integrations to either compute the $\overline{E}$ field or find the reaction

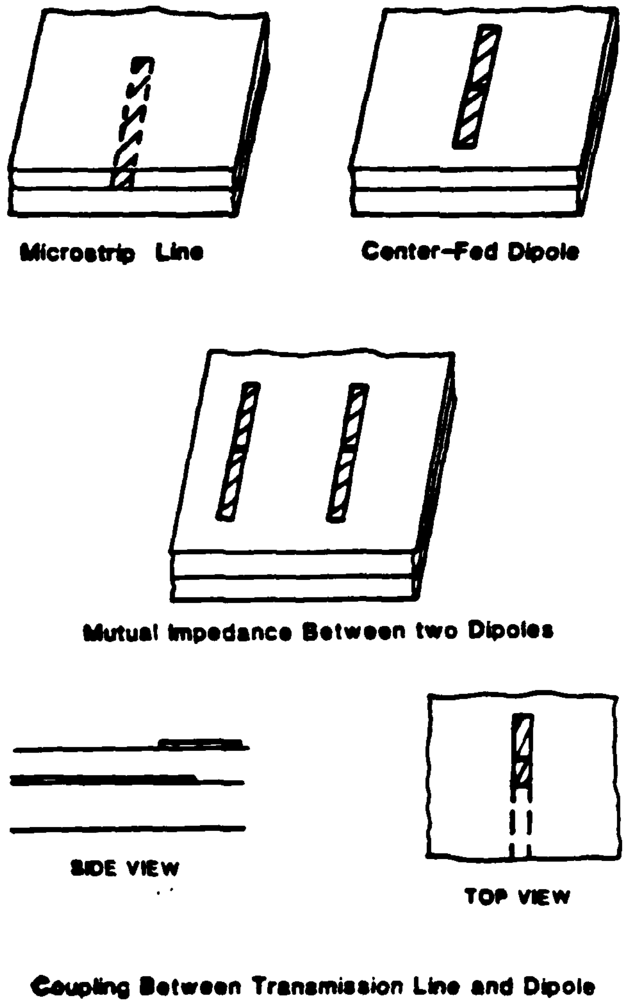



Fig. 2. Four classes of full-size planar strip geometries.

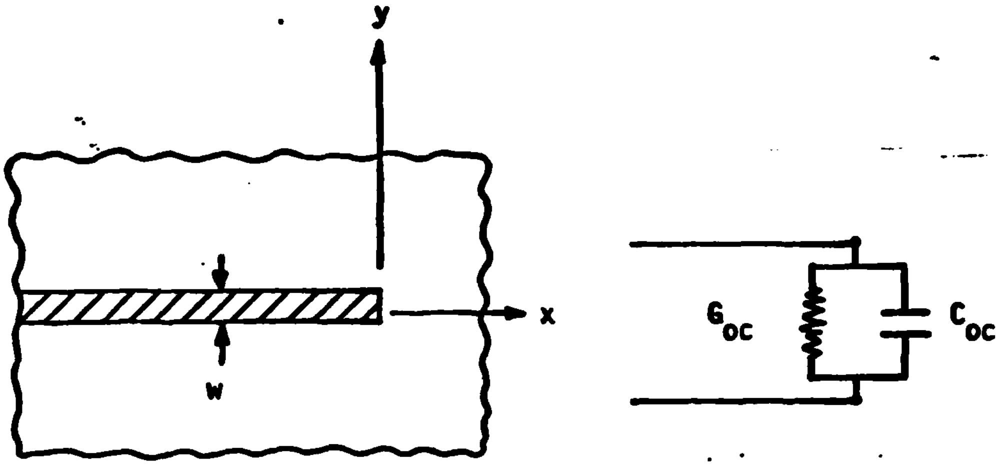
between two current sources. Once the Sommerfeld form of the Green's function has been found in terms of the Hertzian vector potential components, the plane wave spectrum Green's function for the electric field may be found in a straightforward manner, so no rederivation of the Green's function is required. The plane-wave spectrum form of the Green's function allows for a particularly simple formulation of the transmission line problem, in which Denlinger's method is used to obtain a single transcendental equation for the unknown propagation constant on the line.

For the 3-dimensional geometries involving dipoles, a convenient method of analysis is by the Method of Moments, in conjunction with Galerkin's Method. Because of the relative expense involved in using the method of moments, a considerable amount of attention will be devoted to an efficient numerical procedure for computing the reaction between two current basis functions, required in the formulation of the Galerkin matrix. By using the plane-wave spectrum method in conjunction with a filon-type integration scheme, an efficient means of computing the Galerkin coefficients for all the various basis function separations can be developed, which requires a minimum amount of Green's function calculation. An efficient method for the direct evaluation of the Sommerfeld integrals to find the electric field will also be given, in which an asymptotic extraction process is employed to arrive at a rapidly convergent expression which converges for all source and field positions. This method provides for a more efficient computation of the reaction between basis functions which are far apart, and provides a nice compliment to the plane-wave spectrum approach. A matrix storage algorithm will also be adopted in conjunction with the method of moments, to allow for a computationally efficient analysis of the planar structures once a set of Galerkin coefficients has been produced. In this way a systematic study of design configuration can be undertaken at a reasonable cost.

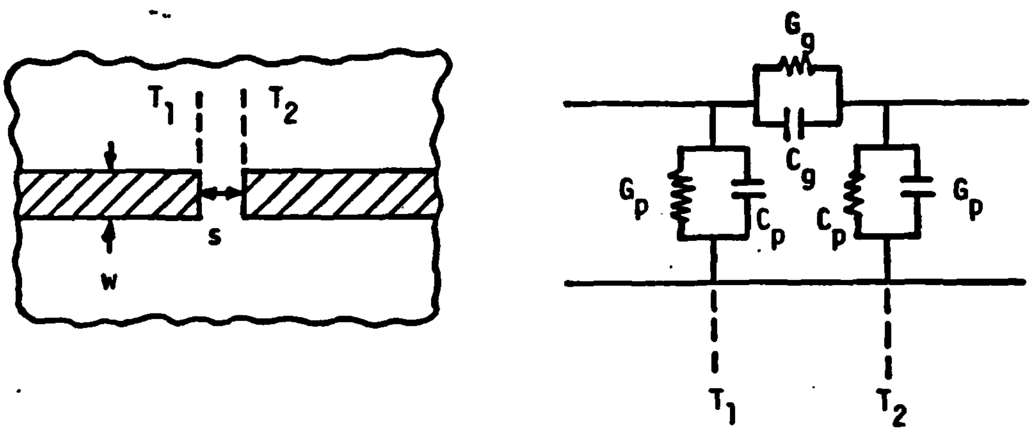
Once the formulation for the planar structures has been given, the effects of a superstrate layer on each of the different configurations previously mentioned will be discussed. For the transmission line, the effect of a superstrate on the propagation constant will be demonstrated. For the center-fed dipole, resonant length and input impedance will be found from the method of moments, and compared with simple approximate formulas which are accurate for short, narrow dipoles. The mutual impedance between dipoles will then be found, first by using the method of moments, and then by using the EMF method. It will be demonstrated that a superstrate layer can have a significant effect on the mutual impedance between dipoles, especially when the dipoles are in an endfire configuration, by reducing or eliminating the surface wave interaction between the dipoles. Finally, the configuration of a dipole excited by means of transmission line coupling will be examined, using the method of moments. This arrangement has been studied in the past both theoretically and experimentally for the case of a single substrate layer as a means of feeding a dipole with a monolithic structure [38]-[42]. By allowing for a superstrate between the line and dipole with different material parameters than the substrate, the amount of coupling between the line and the dipole can be improved. Alternatively, by keeping both the line and the dipole within the substrate with a superstrate on top, the efficiency of both the line and the dipole may be improved. This may be particularly desirable for suppressing unwanted surface wave excitation by the transmission line feeds, which may lead to unpredictable coupling between arrays of such elements.

The literature on the theory of microstrip lines and microstrip discontinuities is extensive but almost without exception the published methods do not account for radiation and discontinuity dispersion effects. Microstrip discontinuity modeling was initially carried out either by quasi-static methods or by an equivalent waveguide model. The former approach gives a rough estimate of the discontinuity parameters valid at low frequencies, while the latter gives some information about dispersion effects at higher frequencies. However, the applicability of the latter model is also of limited value since it does not account for losses due to radiation and surface wave excitation at the microstrip discontinuity under investigation. Therefore, it is reasonable to assume that the data obtained with this model are accurate only at the lower frequency range, i.e., before the radiation losses become significant.

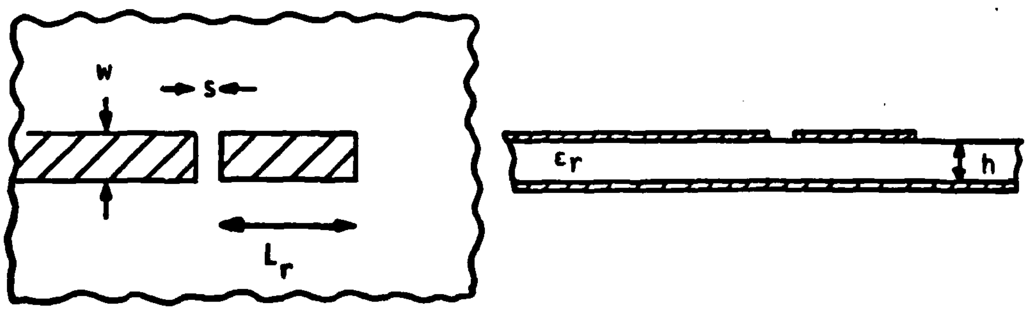
In this research, three types of microstrip discontinuities (Fig. 1) are represented by equivalent circuits with frequency dependent parameters. The implemented method accounts accurately for all the physical effects involved including surface wave excitation. The model developed in this paper also accounts for conductor thickness and it assumes that the transmission line and resonator widths are much smaller than the wavelength. The latter assumption insures that the error incurred by the transverse component of the current distribution on each conducting strip is a second order effect. In each type of discontinuity the method of moments is applied to determine the current distribution in the longitudinal direction, while the current dependence in the transverse direction is chosen to satisfy the edge condition at the effective width location. Upon determining the current distribution, transmission line theory is invoked to evaluate the elements of the admittance matrix for the open-end gap as well as for the resonant frequency of the coupled microstrip resonator (see Fig. 1c). Furthermore, the equivalent circuits for the first two discontinuities are evaluated and compared with the results obtained by a quasi-static method based on the concept of excess length and equivalent capacitance. The quasi-static model does not include the discontinuity's radiation conductance in the equivalent circuits, it yields results which at low frequencies are in good agreement with previously published data. However, a comparison of the quasi-statically obtained results with those of the dynamic model developed in this report shows the inadequacy of the quasi-static approach [43].




(a) Open circuit microstrip line.




(b) Microstrip gap.




(c) Coupled microstrip resonator.

Fig. 1: Microstrip discontinuities and equivalent circuits.

Many materials used as substrates for integrated microwave circuits or printed circuit antennas exhibit dielectric anisotropy which either occurs naturally in the material or is introduced during the manufacturing process. The development of accurate methods and optimization techniques for the design of integrated microwave circuits requires a precise knowledge of the substrate material dielectric constant. It is well recognized that variations in the value of the substrate material relative dielectric constant, as well as possible variations in the value of $\varepsilon$ for different material batches, introduce errors in integrated circuit design and reduce integrated circuit repeatability. For these reasons and because in certain applications anisotropy serves to improve circuit performance, it must be fully and accurately accounted for.

The plurality of substrate materials used for microwave integrated circuits belong to the alumina family. Permittivity variations occurring from batch to batch necessitate repeated measurements for the accurate determination of the dielectric constant; in addition, these materials are slightly anisotropic teflon-type substrates usually ceramic-impregnated which introduces anisotropic behavior. It is known, e.g., that the E-10 ceramic-impregnated teflon (commonly known as Epsilam 10) is anisotropic with a relative dielectric constant $\varepsilon_{yy} = 10.3$ perpendicular and $\varepsilon_{xx} = \varepsilon_{zz} = 13.0$ parallel to the substrate plane. Similar anisotropies are exhibited by a variety of other teflon substrates such as the TFE/Glass Cloth and Loaded TFE/Glass Cloth.

Among the crystalline substrates, single crystal sapphire ($\epsilon_{xx} = \epsilon_{zz} = 9.4$, $\epsilon_{yy} = 11.6$) has attracted considerable attention. Sapphire exhibits several very desirable properties in that it is optically transparent, it is compatible with high resistivity silicon, its electrical properties are reproducible from batch to batch and it exhibits a 30 percent higher thermal conductivity than alumina. On the other hand it is produced in rather small area samples (about 25 mm square) and it is quite expensive. Pyrolitic boron nitride is another anisotropic material suggested for potential use as a substrate for microwave applications. Boron nitride exhibits aniostropy with $\epsilon_{xx} = \epsilon_{zz} = 5.12$ and $\epsilon_{yy} = 3.4$.

There are applications where magnetic anisotropy is employed (as in non-reciprocal devices). For such applications magnetized ferrite materials are used whose magnetic properties are depicted by a second rank tensor permeability $\bar{\bar{\mu}}$. The elements of $\bar{\bar{\mu}}$ are related to the externally applied d.c. magnetic field, microwave frequency, as well as the inherent physical properties of the ferrite material. Recently Microstrip and Finline have been analyzed on ferrite substrate layers.

The basic interaction of Electromagnetic waves with anisotropic materials is well understood. Extensive results exist in the literature for plane wave propagation through anisotropic materials as well as for guided waves in waveguides loaded with gyrotropic slabs. As far as determination of the characteristics of integrated microwave circuits on anisotropic substrates is concerned, however, the existing publications relate mostly to microstrip structures with a few publications on the analysis of coupled slots and slotlines.

The intent of this is to present existing empirical, quasi-static and dynamic solution methods for the derivation of the propagation characteristics for a variety of structures such as microstrip, coplanar waveguides and slotlines. Amongst the quasi-static approaches, the Finite Differences Method, the Method of Moments, and the Variational Principle are emphasized. The Transmission Line Matrix Method, the Fourier Spectrum approach and the Method of Lines constitute the dynamic solution techniques presented in this report. Empirical methods are discussed, a critique of the accuracy and applicability of each approach is given and finally, future research directions are suggested. Details can be found in [44].

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N. G. Alexopoulos and P. B. Katehi, "Efficient Sommerfeld Integral Computation with Application to Printed Circuit Antennas Submitted to URSI Symposium, Boston, MA. 1984

P. B. Katehi " A Generalized Solution to a Class of Printed Circuit Antennas," submitted to the IEEE Symposium, Boston, MA, 1984

N. G. Alexopoulos and P. B. Katehi "Printed Circuit Antennas for Microwave and Millimeter Wave Applications", 1st International Telecommunications and Control Conference Digest, August 20-25, 1984, Halkidiki, Greece.

Attended the U.S. Army Millimeter Wave Workshop at N.Y.I.T. December 1984.

D. R. Jackson and N. G. Alexopoulos "Microstrip Dipoles on Thick Substrates", SPIE Conference, April 1985, Washington, D.C.

P. B. Katehi and N. G. Alexopoulos, "Microstrip Discontinuity Modelling for Millimetric Integrated Circuits" IEEE Micwowave Theory and Technique International Symposium Digest, pp. 571-573, June 4-6, 1985, St. Louis, Missouri.

D. R. Jackson and N. G. Alexopoulos, "Characteristics of Microstrip Antennas with a Superstrate", IEEE AP-S International Symposium Digest pp. 89-91, June 1985.

D. R. Jackson and N. G. Alexopoulos, "Characteristics of Microstrip Antennas with a Superstrate," IEEE AP-S International Symposium Digest, pp. 405-408, Vancouver, Canada, June 17-21, 1985.

P. B. Katehi and N. G. Alexopoulos, "A Generalized Algorithm for the Modeling of the Dispersive Characteristics of Microstrip, Inverted Microstrip, Stripline, Slotline, Finline and Coplanar Waveguide Circuits on Anisotropic Substrates, "IEEE MTT-S International Microwave Symposium DIgest, pp. 457-459, St. Louis, U.S.A., June 4-6, 1985.

P. B. Katehi and N. G. Alexopoulos, "Microstrip Discontinuity Modelling for Millimetric Integrated Circuits," IEEE MTT-S International Microwave Sympoisum Digest, pp. 571-573., St. Louis, U.S.A., June 4-6, 1985.

D. R. Jackson and N. G. Alexopoulos (Invited), "Microstrip Dipole Antennas on Electrically Thick Substrates, "SPIE Proceedings, vol. 544, April 9-10, 1985.

## HONORS

### Best Paper Award

The S. E. Schelkunoff Award (Best Paper Award by the IEEE Antennas and Propagation Society) for the paper by P. B. Katehi and N. G. Alexopoulos, "On the Modeling of Electromagnetically Coupled Microstrip Antennas - The Printed Strip Dipole, "IEEE Transactions on Antennas and Progagation , vol. 32, pp. 1179-1186, November 1984.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DIRING THIS REPORTING PERIOD:

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