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Our studies have shown the development of several ways of accurately yet efficiently modelling the behvavior of closely spaced microstrip antenna elements. The accuracy has been verified by comparison with "brute force" numerical procedures, and thus suggests that wideband microstrip antennas should be designable with much less difficulty than previously believed.

Further, both experimental and numerical evidence has been obtained for the proposition that wider bandwidth, and even lower frequency operation of a microstrip patch antenna element can be achieved by arranging many closely coupled narrow strip dipoles together in an appropriate way. We are far from a complete understanding of these effects; especially there has been no study of the frequency dependence of the radiation properties of these new elements. Design and optimization of them is also in a very primitive stage, as accurate modeling of their properties requires numerically intensive methods at this time. Questions of this nature deserve more investigation.

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1 Final Report—Contract No. N00014-86-K-0417

Contract Title:	Investigation of Broadband Microstrip Antenna Structures for Application in Monolithic Millimeter Wave Arrays
Number:	N00014-86-K-0417
Principal Investigator:	David C. Chang Department of Electrical and Computer Engineering University of Colorado Boulder, Colorado 80309-0425 Telephone: (303) 492-6702
Program Manager:	Dr. Yoon Soo Park

2 Technical Objectives

The main objective of this research project is to investigate broadband microstrip antenna structures. We believe the bandwidth limitation of these antennas is unnecessarily inhibited by theories and practices based on conventional antenna concepts. It has not been fully appreciated by researchers in the field that the flexibility inherent in computer-generated layouts and photolithography fabrication processes provide us with an unprecedented opportunity to explore new antenna forms as well as novel array architectures.

3 Approach

The underlying theme of this research is the idea that many closely coupled strips with slightly differing individual resonances should be able to serve as a composite element with a much wider bandwidth. For instance, a microstrip implementation of the log-periodic antenna array concept should be possible using far less area than previous approaches have done.

Based on several canonical problems, we have developed efficient and accurate algorithms to analyze patch antennas. A generalized edge boundary condition (GEBC) has been introduced as a tool to study various configurations. This GEBC not only takes into account local edge effects, but also the coupling above the patch and surface and radiation wave effects as well. We have also made use of a numerical (moment-method) modeling code developed in our group for another project which allows accurate computation of currents on microstrip patches of moderate complexity. This has served as a check on the other more efficient computational tools we have employed, as well as on the interpretation of experimentally measured data.

An approximate modeling technique has also been used based on an equivalent boundary condition for the averaged fields at a finely slotted conductor.

We avoid the need to compute, in detail, the complicated current distribution on each of many closely spaced strips in this way, and instead use a sort of "impedance sheet" smoothed description of a patch which is slotted in this way.

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4 Accomplishments

4.1 Strongly Coupled Patch Antennas

The GEBC approach as previously developed by us was extended to handle patches with narrow slots in them. Like previous GEBC methods, this one allows the modelling of the patch by a one-dimensional (line) integral equation rather than a two-dimensional (surface) one. The reduction in computational effort is substantial, yet we still achieve good accuracy as shown by comparison with both experimental and other theoretical work. This program is now in a well documented and modular form at the Electromagnetics Laboratory, and serves as a source of comparison data for other models used in this study.

4.2 Multiply-Coupled Microstrip Dipole Antennas

Microstrip antennas are attractive for their compactness and conformability, but usually have a bandwidth of only a few percent. We have investigated a novel type of antenna, based on a "multi-resonance" technique. In this approach, the idea is to couple n strip dipoles of slightly different lengths, and to overlap the n resonances.

A simple theoretical model based on transmission line equations was used first for the case of 2 or 3 coupled lines. The radiation losses on each line are taken into account by loading both ends with an equivalent lumped admittance determined separately from a numerical method. This model permits us to use the TOUCHSTONE program to optimize the input impedance versus frequency. Optimization is carried out by variation of strip lengths, strip separations and strip widths.

For two strips of equal length, there are two modes on the coupled line section: an even (or antenna) mode, where the voltages on the strips are equal and in phase, and an odd (or transmission-line) mode where the voltages have the same amplitude but are 180° out of phase. The odd mode currents tend to produce fields which cancel each other out in the far field, producing little radiated power and a bandwidth around the resonant frequency that is too small to be of use for wideband applications.

When one of the strips is lenghtened slightly, significant coupling is introduced at the line ends between the even and odd modes, and the resonances of the system of coupled lines are thus broader than that of the odd mode of the symmetric structure. Adjustment of the parameters of the coupled lines is then possible to overlap these resonances and produce an overall larger bandwidth for the antenna.

Similarly, it was found that if the strips have the same widths, then significant overlapping of the individual resonance curves occurs only for large strip separations. For asymmetrical lines on the other hand, there is greater control over the normal mode propagation constants, and thus over the resonant frequencies. We find that width and separation of the lines are the most sensitive parameters of the structure.

To overcome the necessity to have large strip separations, we have studied the effect of connecting elements together by short sections of line. Such a connection acts as a short circuit to the odd mode on a pair of strips of equal width, and provides a means of additional control on the antenna resonances (the even mode is affected very little by such bridges). In this way a wider bandwidth can be achieved while maintaining a compact structure.

Initial design and optimization was done based on this simple transmission line model using TOUCHSTONE, and gave some promising results. Figure 1 shows a two-strip element with unequal lengths achieving a predicted bandwidth of almost twice that of a single narrow-strip dipole radiator. This comes about with an input impedance tracing out a Smith chart locus that loops near the origin, increasing the frequency range where the element radiates significantly for a feed line of given impedance.

This design was also analyzed with the more accurate in-house moment method code. Comparison with the transmission-line model shows that accurate determination of equivalent network parameters for the coupled line ends is of paramount importance, and must be improved in order for the simpler model to have utility in practical design situations. In Figure 2, we see that the TOUCHSTONE code and moment method results are in good agreement when computing input impedance for a single strip. However, in Figure 3, we see that the same comparison for two coupled strips (with a terminating network identical to that obtained for the single strip used in the TOUCHSTONE analysis) is quite poor.

A direct use of the moment method code for the analysis of such a structure is possible, but requires too much computer time to be of use in design or optimization. The alternative (which should be the subject of future research) is to use the moment method code to find the equivalent end network for terminated coupled lines, store this information in a look-up table, and use it together with the transmission line analysis to design and optimize the structure. The possibility of large amounts of computer time still exists, but the look-up table along with some sort of interpolation process should help that problem substantially.

4.3 One-Dimensional Current Modeling of Microstrip

Narrow microstrip lines and antenna elements have current distributions substantially directed only along the direction of the conductor. General numerical schemes for the analysis of microstrip antenna structures have often not taken advantage of this fact, and require much more computer time and storage in order to analyze such structures. We have developed a numerical (moment) method based on this simplified representation of the current on the strip to handle such things as L-bends, microstrip antenna feeds, and so on. Accuracy for this approach has been demonstrated in the case of the L-bend S-parameters,

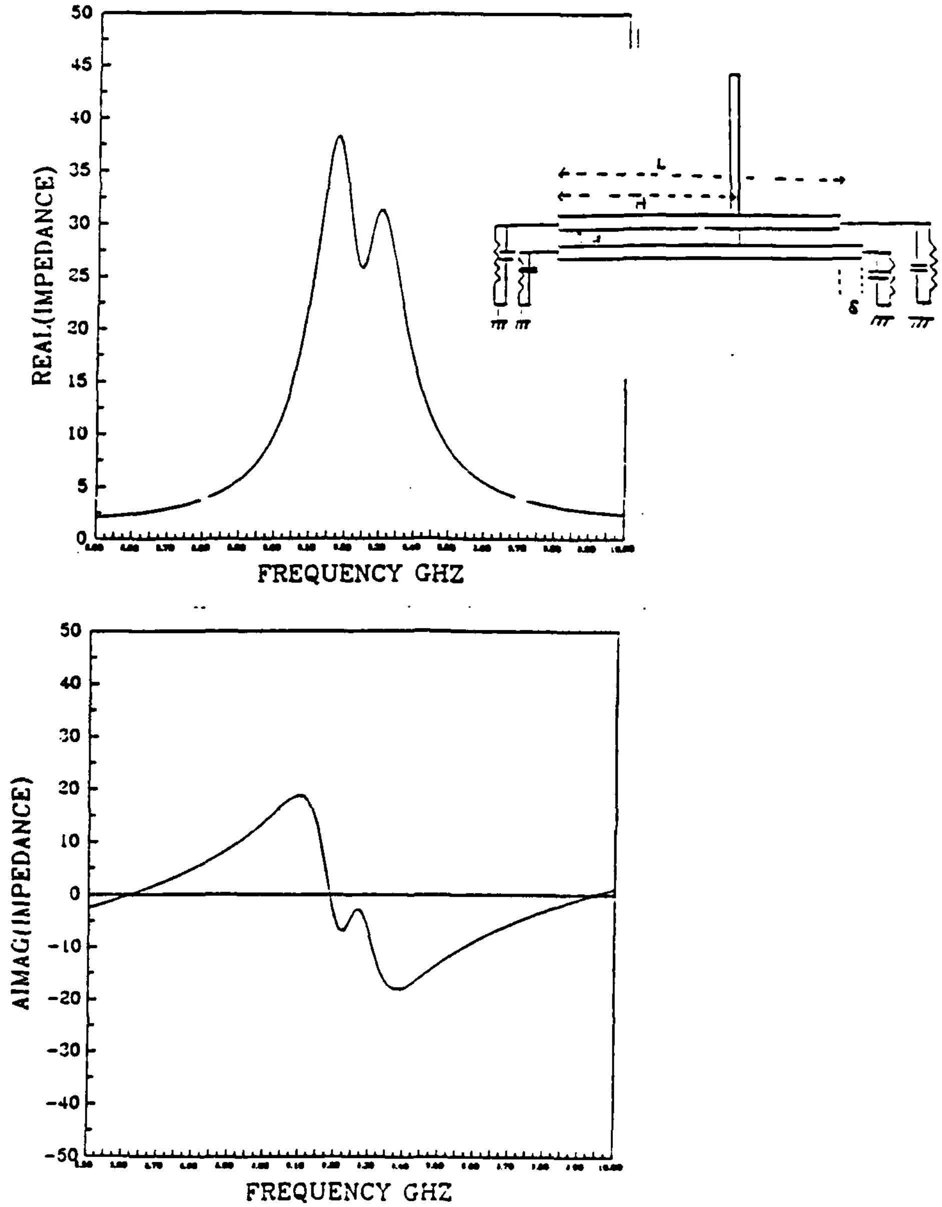


Figure 1 Transmission line analysis
d=.7mm H=7.8mm L=14.67mm
δ=.15mm ε_r=1.

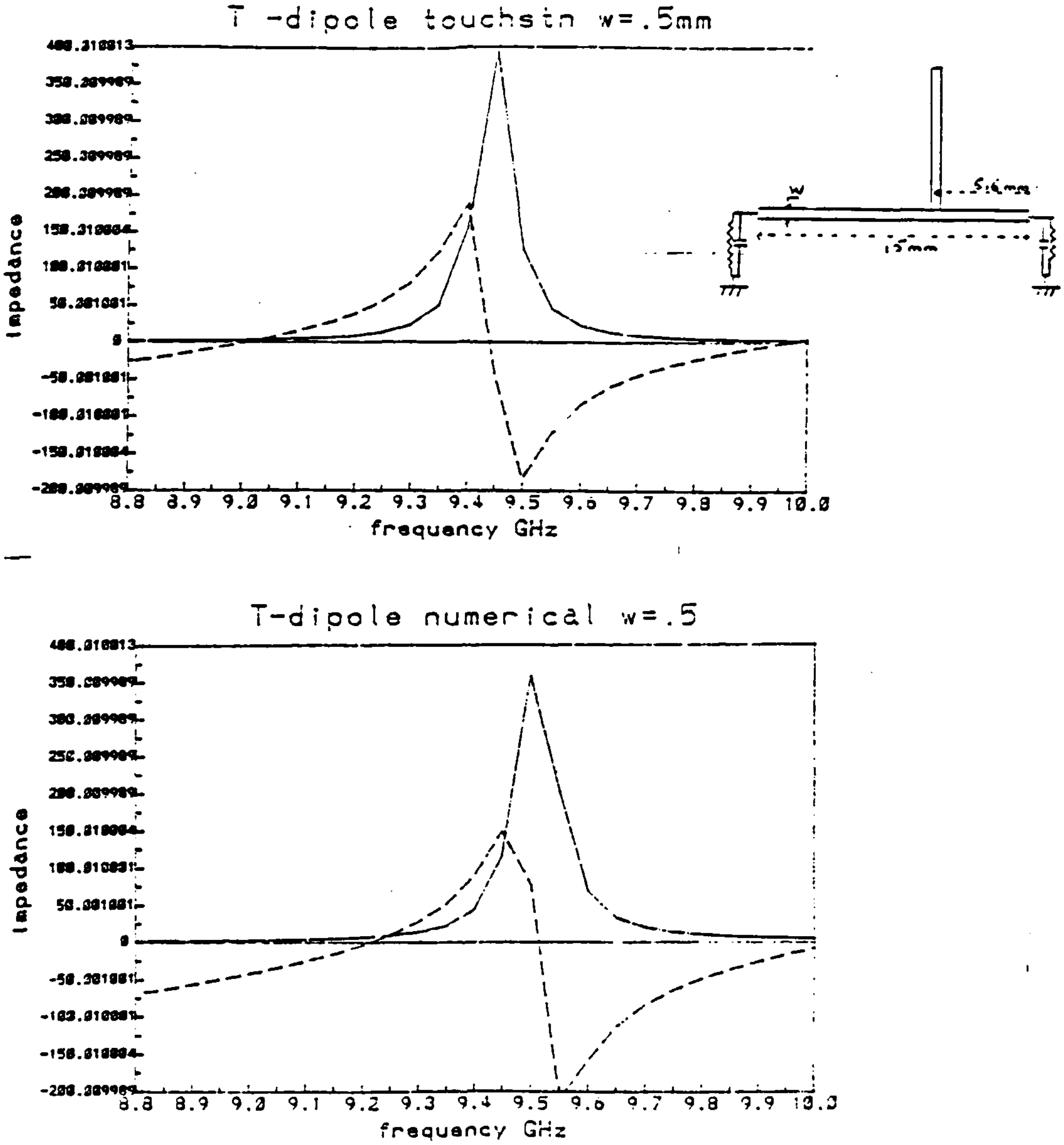
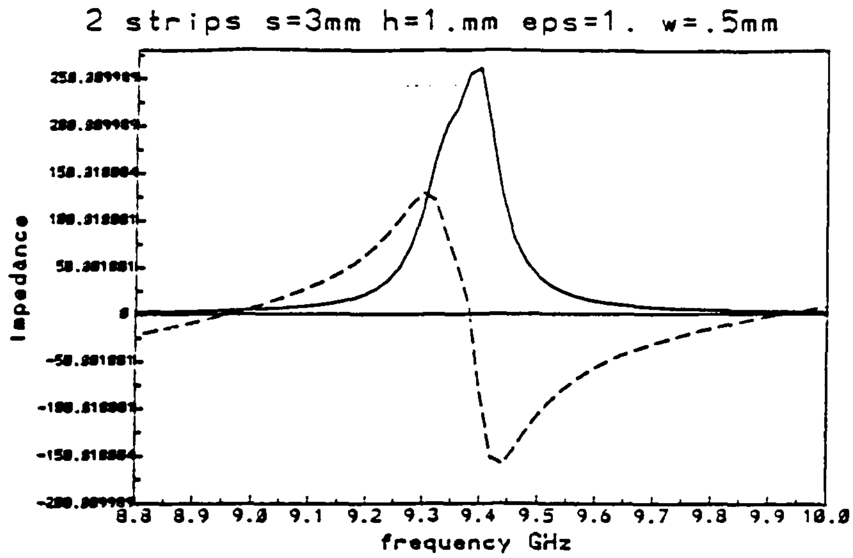


Figure 2 single dipole
a -computation by Touchstone
b - Moment method
w=.5mm h=1.mm ε_r*=1.0*



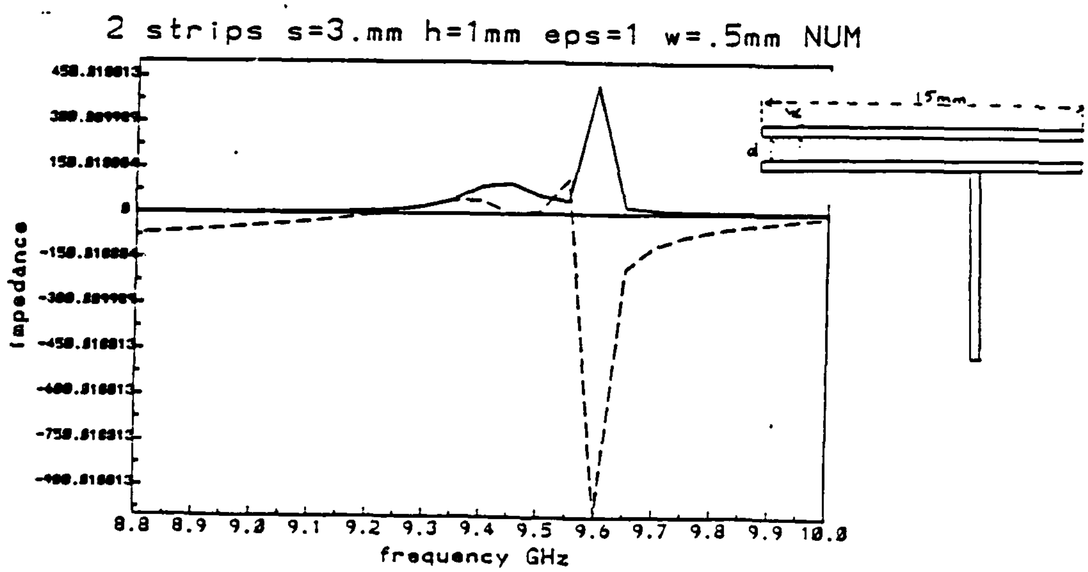


figure 3 2 coupled strips
a - computation by Touchstone
b -Moment method
d=3mm h=1.mm w=.5mm $\varepsilon_r=1.0$

and the method was used in the moment method analyses reported above in order to save on computation time.

4.4 Surface Waves on a Strip Grating on a Grounded Substrate

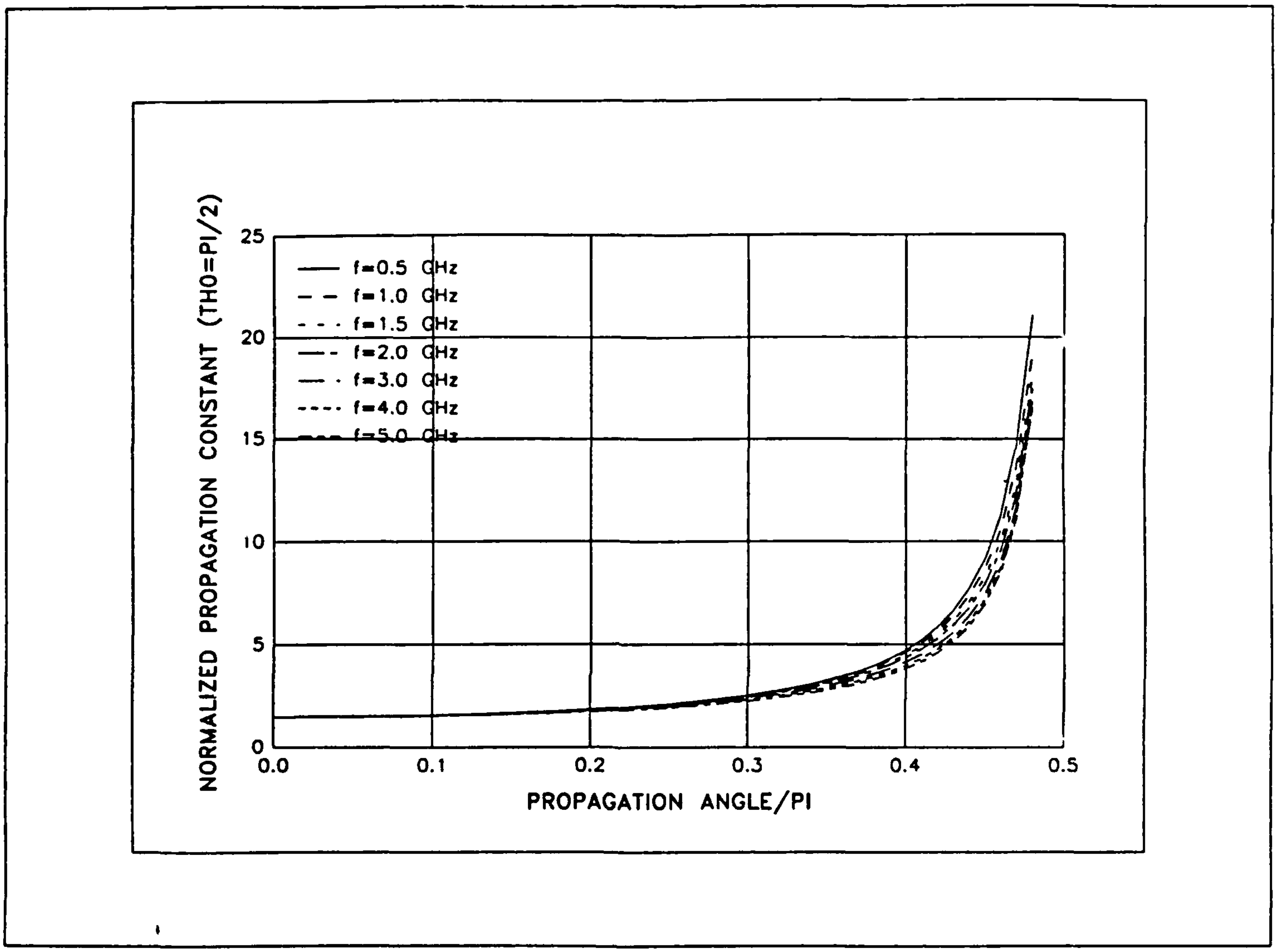
An alternate approach to the analysis of microstrip antennas consisting of many closely coupled strips has been developed. Neither "exact" moment method techniques nor coupled transmission line theory is very promising as an efficient means of computing the characteristics of antennas of this type. The number of unknowns becomes prohibitively large, and the accuracy of the model is drawn into some question. We have investigated the use of *equivalent* or *averaged* boundary conditions at a surface containing a dense grating of strip conductors whose dimensions are small compared to a wavelength. These are applied to the average field, and do not require a knowledge of the detailed fine structure of the field between or on the strips.

These conditions have been used to obtain the propagation constants of a surface wave on an infinite grating of strips on the surface of a grounded dielectric substrate. We find that the propagation constant is a function of the angle of propagation relative to the axes of the strips, as shown in Figure 4. Good agreement has been obtained with previously calculated numerical results, which is encouraging to us for application of this method to more complex antenna structures. A point to notice is the fact that the propagation constant starts out near $k_0\sqrt{\epsilon_r}$, where k_0 is the freespace wavenumber, and ϵ_r is the relative permittivity of the substrate, for propagation parallel to the slots. This increases with increasing angle to the slots, slowly at first, but quite rapidly as the angle nears 90°. Before 90°, however, the wave becomes leaky, acquiring a large attenuation constant with further increase in propagation angle.

Because of this anisotropic propagation behavior of the surface wave, a transverse resonance analysis of the properties of a rectangular slotted patch (using magnetic wall conditions to approximate current behavior at the edges) predicts that several closely spaced and narrow resonances will appear around the frequencies where the unslotted patch had only a single resonant mode. These modes have standing waves in the direction transverse to the slots and current flow, with a large number of half-wavelengths possible for the higher modes in the set. This behavior has been confirmed by the moment method analysis, as shown in Figure 5.

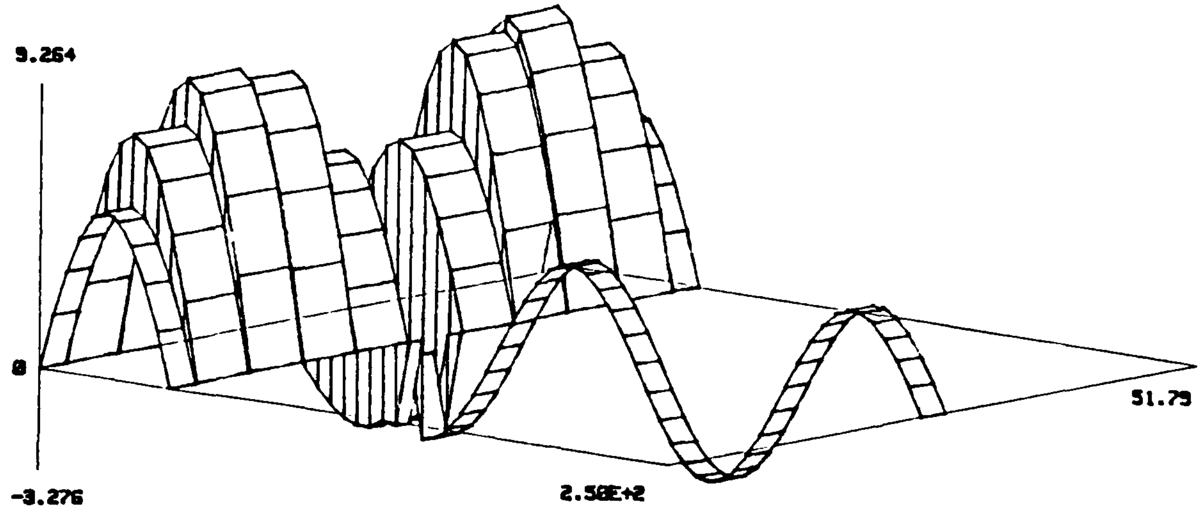
The behavior of such slotted patches has been measured experimentally on an HP 8510 Automatic Network Analyser. The patch was 2" square on a substrate of permittivity $\epsilon_r = 2.2$ as shown in Figure 6. An SMA connector was attached to the 50 Ω microstrip feed line, and the reflection coefficient S_{11} was measured over the range from 500 MHz to 8 GHz. Slot angles of 0°, 45°, and 90° with respect to the feed line were tested, along with an unslotted patch.

The unslotted patch (Figure 7) shows resonances closely agreeing with those predicted by a simple cavity model; the lowest mode appears at $f \simeq 2$ GHz. A

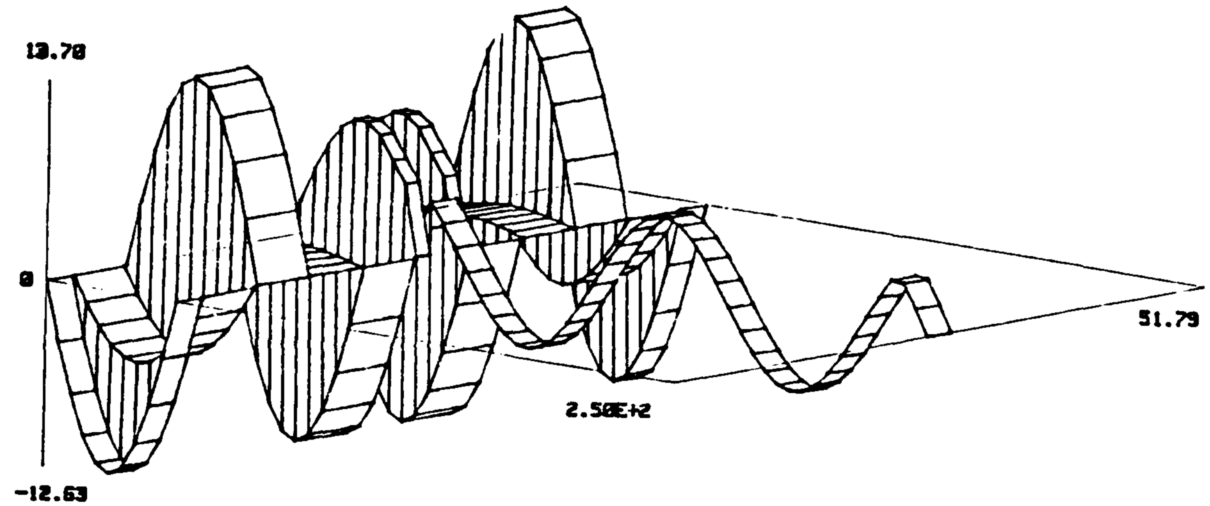


NORMALIZED PROPAGATION CONSTANT (TH0=PI/2)
25
20
15
10
5
0
0.0
0.1
0.2
0.3
0.4
0.5
PROPAGATION ANGLE/PI
f=0.5 GHz
f=1.0 GHz
f=1.5 GHz
f=2.0 GHz
f=3.0 GHz
f=4.0 GHz
f=5.0 GHz

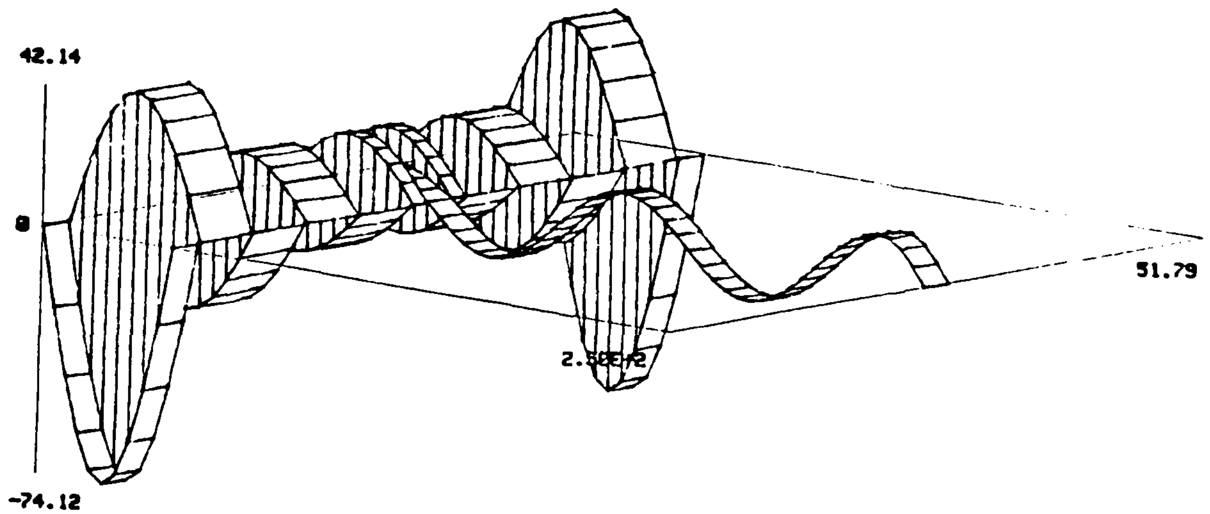
Figure 4:



9.264
0
-3.276
2.50E+2
51.79



13.70
0
-12.63
2.50E+2
51.79



42.14
0
-74.12
2.50E+2
51.79

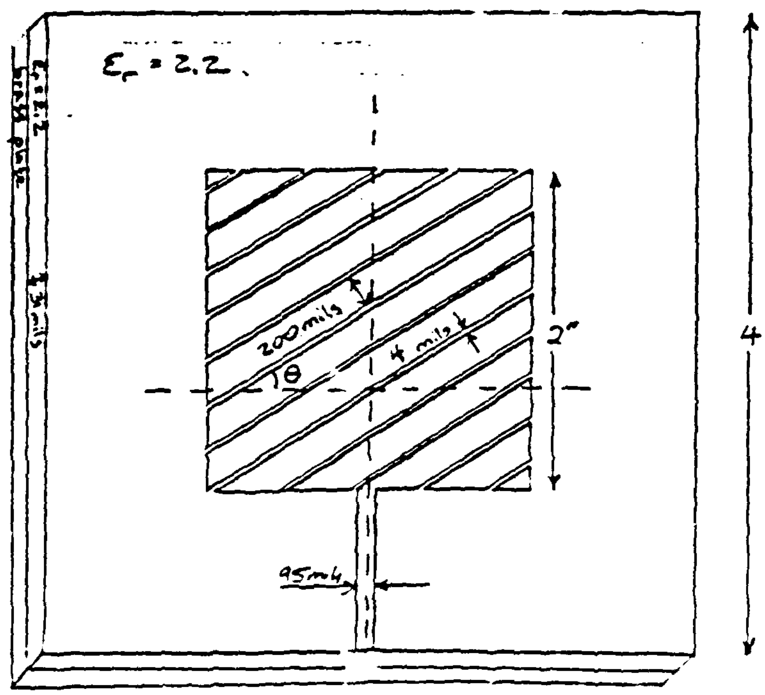
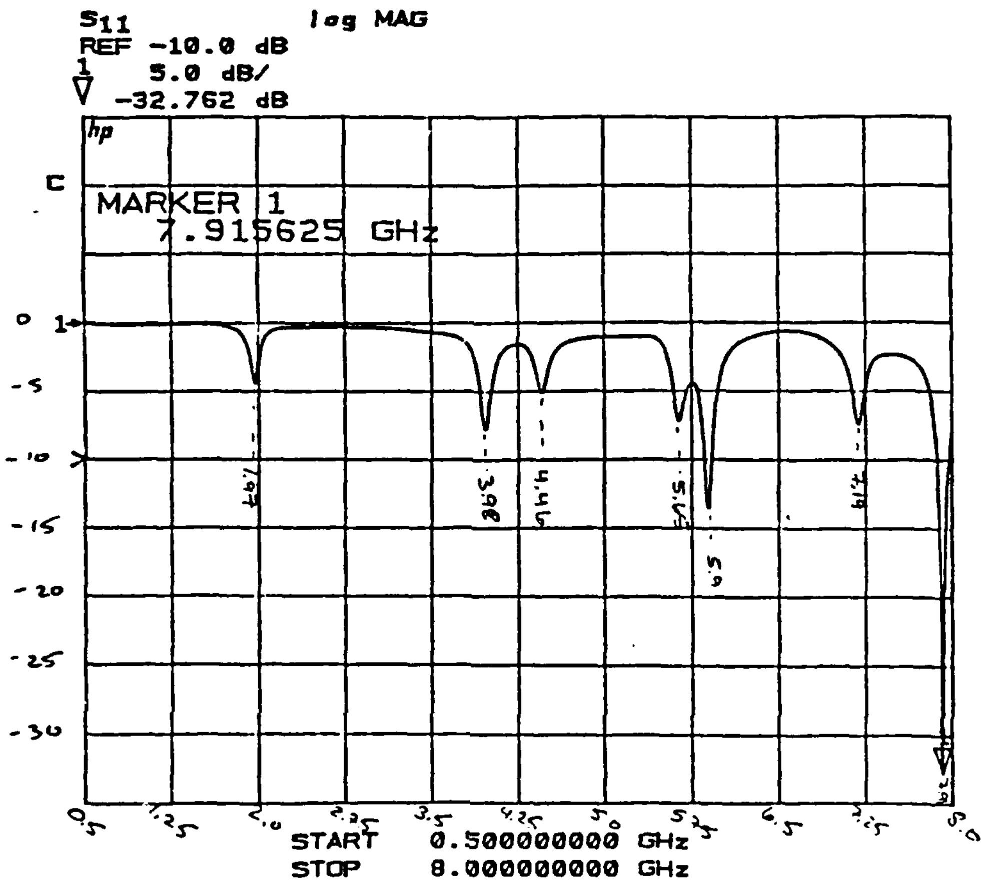


Figure 6:



S11
log MAG
REF -10.0 dB
1 5.0 dB/
-32.762 dB
hp
C
MARKER 1
7.915625 GHz
0
-5
-10
-15
-20
-25
-30
0.5
1.25
2.0
2.75
3.5
4.25
5.0
5.75
6.5
7.25
8.0
1.97
3.98
4.46
5.9
7.19
START 0.500000000 GHz
STOP 8.000000000 GHz

Figure 7:

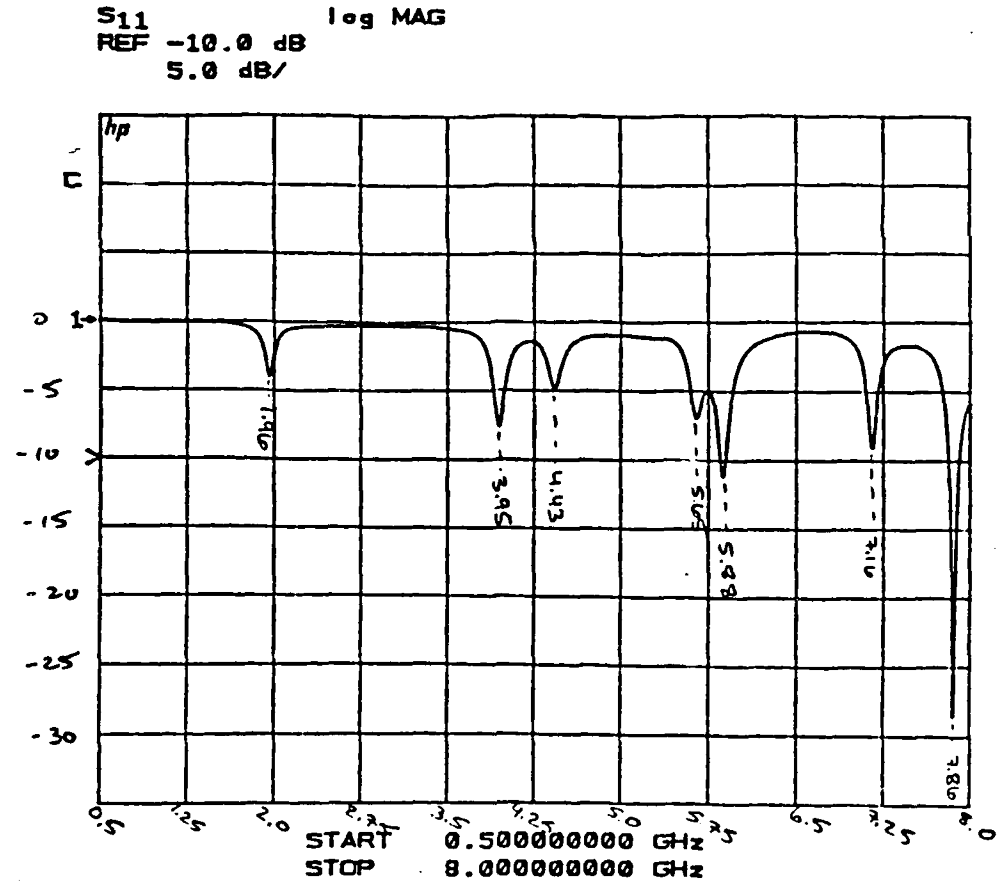


Figure 8:

patch with 45° slots measures nearly identical to the unslotted patch (Figure 8). This is explained by the fact that the unslotted square patch has degenerate modes of the same resonant frequency which differ only in the perpendicular orientations of their current distributions. An equal combination of these degenerate modes is therefore possible which has its currents flowing completely parallel to these slots, and therefore relatively undisturbed by them. Slots parallel (0° to the feed line) produced the reflection coefficient shown in Figure 9. The "line-splitting" predicted above by the theoretical model is observed; resonant frequencies are predicted within about 1% by the moment method code, ana a few percent by the transverse resonance model using the grating surface wave.

Slots perpendicular to the feed line (90°) produce a very different spectrum of modes as shown in Figure 10. There are some resonances of unusually low

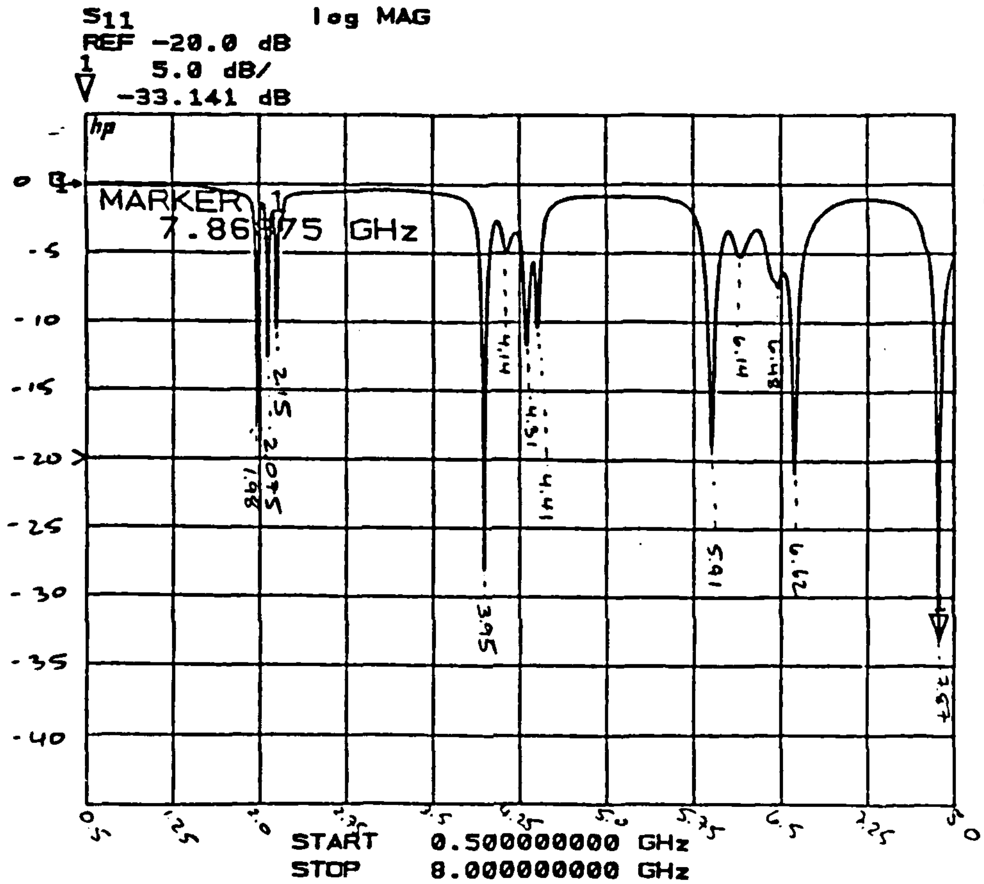
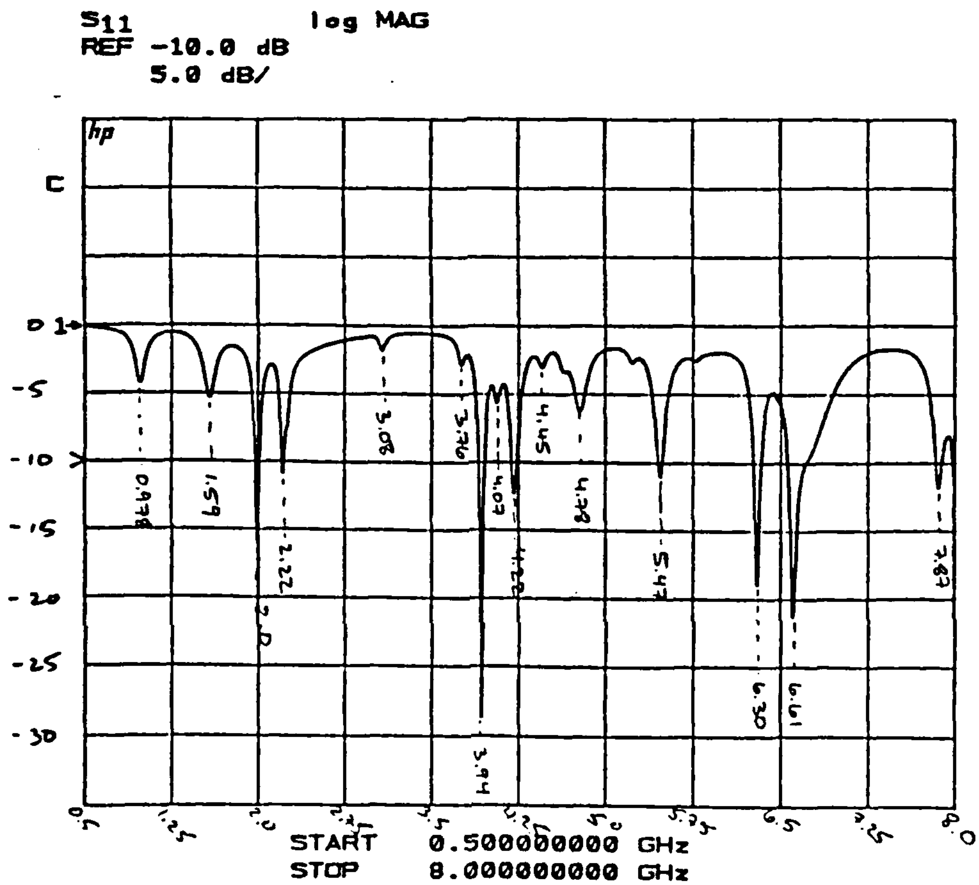

S11 log MAG
REF -20.0 dB
1 5.0 dB/
-33.141 dB
MARKER 1
7.86875 GHz
START 0.500000000 GHz
STOP 8.000000000 GHz

Figure 9:



S11 log MAG
REF -10.0 dB
5.0 dB/
hp
START 0.500000000 GHz
STOP 8.000000000 GHz

Figure 10:

frequency; the lowest is at less than one-half that of the unslotted patch, and cannot be accounted for by the traditional model of a standing wave in the dielectric under the patch. The high propagation constants possible at perpendicular propagation for the grating surface waves suggest these as a possible explanation, but a transverse resonance analysis of this structure fails to locate any such resonant frequency. Likewise, the moment method code (pushed to as fine a mesh of cells as can be solved on our HP 300 series workstations) also fails to find such a resonance. Some possible explanations have been discussed, but no evidence yet exists to support any of them, and further experimental work, as well as numerical work (building a moment method code based on the average field boundary condition rather than the exact slotted conductor geometry) should be done to answer this very curious question. The anomalous resonances, though not strong, are reasonably wide, and could be of some practical importance in achieving wideband patch operation.

5 Significance:

Our studies have shown the development of several ways of accurately yet efficiently modelling the behavior of closely spaced microstrip antenna elements. The accuracy has been verified by comparison with "brute force" numerical procedures, and thus suggests that wideband microstrip antennas should be designable with much less difficulty than previously believed.

Further, both experimental and numerical evidence has been obtained for the proposition that wider bandwidth, and even lower frequency operation of a microstrip patch antenna element can be achieved by arranging many closely coupled narrow strip dipoles together in an appropriate way. We are far from a complete understanding of these effects; especially, there has been no study of the frequency dependence of the radiation properties of these new elements. Design and optimization of them is also in a very primitive stage, as accurate modeling of their properties requires numerically intensive methods at this time. Questions of this nature deserve more investigation.

6 Publications and Presentations:

6.1 Publications

T. M. Martinson and E. F. Kuester, "Accurate analysis of arbitrarily shaped patch resonators on thin substrates," *IEEE Trans. Micr. Theory Tech.*, vol. 36, pp.324-331, 1988.

E. F. Kuester and F. Bellamine, "Surface waves along a grating on a grounded dielectric substrate," Scientific Report, Electromagnetics Laboratory, University of Colorado, Boulder, in preparation.

F. Bellamine and E. F. Kuester, "Geometrical theory of finely slotted microstrip patches," Scientific Report, Electromagnetics Laboratory, University of Colorado, Boulder, in preparation.

6.2 Presentations

B. Brim and D. C. Chang, "Feed modeling for microstrip patch antennas," *1988 URSI Radio Science Meeting*, 6-10 June 1988, Syracuse, NY, p. 84.

T. M. Martinson and E. F. Kuester, "Efficient analysis of strongly coupled patch antennas," *1988 URSI Radio Science Meeting*, 6-10 June 1988, Syracuse, NY, p. 81.

A. Hoorfar, D. C. Chang and E. Penard, "Multiply-connected microstrip dipole antennas," *1989 National Radio Science Meeting*, 4-6 January 1989, Boulder, CO, p. 119.

B. Brim, D. C. Chang and D. Wu, "Input impedance of a microstrip-fed rectangular patch antenna," *1989 URSI Radio Science Meeting*, 26-30 June 1989, San Jose, CA, p. 206.

E. F. Kuester and F. Bellamine, "Surface waves on a grating above a grounded dielectric slab," submitted to 1990 National Radio Science Meeting, January 1990, Boulder, CO.

7 Participants:

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Ahmad Hoorfar (Research Associate)
Elisabeth Penard (Research Associate)
Thomas Martinson (Graduate Student)
Fethi Bellamine (Graduate Student)
J.-X. Zheng (Graduate Student)

Dr. Martinson received his Ph. D. degree in August 1988, and is now with Ascom Tech in Berne, Switzerland.

Dr. Hoorfar is now Assistant Professor of Electrical Engineering at Villanova University in Philadelphia, Pennsylvania.

Dr. Penard is now with CNET in France.