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Microwave and Millimeter-wave Propagation in Photonic Band-Gap Structures

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Abstract

Electromagnetic wave propagation in periodic dielectric media is analogous to electron-wave propagation in crystals. From solid-state theory, we know that semiconductors allow electron conduction without scattering only in certain "band-gaps." Early work at optical frequencies successfully demonstrated that light propagation could be inhibited in certain frequency gaps in special photonic crystals. Carrying this idea into the macroscopic world, preliminary results suggest that microwave and millimeter-wave frequencies could be also be manipulated by carefully designing and fabricating photonic structures composed of regions of differing dielectric constants. This inhibition of electromagnetic wave propagation in periodic dielectric media is due to interference effects between the alternating regions of high and low dielectric constants.

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"What we need is imagination, but imagination is a strait-jacket. We have to find a new view of the world that has to agree with everything that is known, but disagree in its predictions somewhere, otherwise it is not interesting. And in that disagreement it must agree with nature. If you can find any other view of the world which agrees over the entire range where things have already been observed, but disagrees somewhere else, you have made a great discovery. It is very nearly impossible, but not quite ... a new idea is extremely difficult to think of. It takes a fantastic imagination."

- Richard Feynman, *The Character of Physical Law*, 1965

"If only it were possible to make dielectric materials in which electromagnetic waves cannot propagate at certain frequencies, all kinds of almost-magical things would happen."

- John Maddox, *Nature*, 1990

Contents

1 Purpose

This report is a description of the progress to date on modeling high efficiency microwave antennas and circuits with specially designed artificial substrates. Planar antennas are ideal for high frequency applications being both conformal and easily integrated into thin-film circuits. Unfortunately, they usually have low gain and high ohmic and/or dielectric losses. Since high-density materials are routinely used in the fabrication of these devices, a surface wave suppression technique involving the use of artificial substrates is investigated as a means to increase radiation efficiency.

2 Preliminary Results

How can surface wave losses be eliminated in planar circuits and antennas? Micromachined substrates, dielectric lenses, and photonic band-gap (PBG) materials are three of the candidate technologies that are currently being investigated at the University of Michigan Radiation Laboratory for use in surface wave suppression. Photonic band-gap structures are found to have unique properties that are advantageous in applications involving semiconductor integrated circuits [5]. Such structures offer the advantage of changing the physical properties of substrates used in fabricating planar circuits. A number of applications for such a structure can be imagined including dielectric mirrors, resonant cavities, high Q filters, isolators, dielectric waveguides, couplers, and frequency selective surfaces (FSS).

2.1 Theoretical

Our primary goal is to develop 2-D and 3-D models that can be used to characterize inhomogeneous or periodic substrates. Specifically, we are interested in modeling the effects of substrate geometry and metalization on substrate properties such as surface wave formation. For simple structures, one can theoretically determine the eigenvalues and subsequently the band-gap regions of the system. In order to determine the frequencies of interest for a complex structure, a full-wave, doubly periodic, IE/MoM code is being developed to determine the eigenvalues of a two-dimensional, inhomogeneous dielectric region. This region is then used as a unit cell of a three-dimensional structure. By using the periodicity of the unit cell, one can model the photonic structure and determine the desired band-gaps. In addition, a full 3-D simulation of each structures has been carried out using a finite element analysis.

2.2 Experimental

In parallel to the theoretical modeling, experimental studies with micromachined dielectrics were carried out to corroborate the theoretical values for the band-gaps. A one-dimensional periodic dielectric substrate has been fabricated and tested to see if the band-gap predicted by coupled-mode theory exists for microstrip excitation. After establishing the existence of this band-gap in one-dimensional structures at microwave frequencies, many different two-dimensional lattice structures including the square, hexagonal, and rectangular lattices, have been fabricated and tested. Results from these experiments are included in the presentation found in the Appendix [4].

3 Observations

As can be clearly seen in the Appendix, the so-called photonic band-gaps are indistinguishable from simple filtering mechanisms. Inherently, photonic band-gaps are a large scale phenomena requiring hundreds of periods of alternating dielectric material to achieve the desired frequency gaps. However, it is unclear at the present time however whether photonic band-gaps even exist in finite structures. It is also unclear whether the current phenomena is reproducible for more complicated structures.

Experimental and computational evidence indicates that the high-density material used to support microstrip circuits confines the field to near the microstrip itself. Thus, the circuit simply "sees" a periodically changing dielectric constant – a simple hi-Z, low-Z filter. For the data shown in the Appendix, the measured data were obtained using an HP8510 Network Analyzer. The circuits were fabricated using Rogers Duroid with a relative dielectric constant of 10.2. The finite element (FE) simulation was carried using HP's High-Frequency System Simulator (HFSS) for the exact structure of interest. The Libra simulation was designed for the appropriate circuit model over a periodic dielectric material (hi-Z, low-Z filter).

Notice the good agreement in the data for the microstrip circuits. Each predicted the correct gap. Material was then removed successively from the 1-D periodic dielectric slab to a finite 1-D grating, to a checkerboard pattern, to finally, the 2-D cylinder pattern. Note again the excellent agreement between computation and measurement. The above results were also obtained using a coplanar waveguide (CPW) circuit. It should be noted here that the Libra model for CPW is not good. The data obtained from the Libra simulation for this circuit is questionable. However, the HFSS simulation again agreed with the measured results. But, is this a *photonic band-gap*? Or is it simply a filter?

4 Future Work

Future work in the computational area should include metalizing the holes and/or dielectric cylinders, metalizing the cover layer to include antennas and other more interesting circuit components, coupling the problem with printed circuits, and the convergence issue of the IE/MoM code. A number of experiments are being designed and fabricated in order to understand the filtering mechanisms and surface wave formation in more complex substrates.

5 Suggested Reading

For the interested reader, a number of sources may be used to begin to understand band-theory in solids and the analogous problem of electromagnetic wave propagation in periodic dielectric media. The seminal work that rekindled excitement in photonic band-gap research can be found in Yablonovitch's 1987 paper [5]. Excellent reviews of photonic band-gap research carried out before 1994 can be found in special issues of the *Journal of the Optical Society of America B* [8] and the *Journal of Modern Optics* [9]. Brown *et al.* investigated the radiation properties of a planar antenna on a photonic crystal [1]. Recently, a book outlining photonic band theory and covering a wide range of photonic crystal applications was published by Joannopoulos [3]. Recent numerical work in determining theoretical band-gaps for microwave applications was done by Yang [6, 7].

References

[1] Brown, E.R., C.D. Parker, and E. Yablonovitch, "Radiation properties of a planar antenna on a photonic-crystal substrate," *J. Opt. Soc. Am. B*, vol. 10, no. 2, pp. 404-7, 1993.

[2] Feynman, R.P *The Character of Physical Law*, M.I.T. Press: Cambridge, 1965.

[3] Joannopoulos, J.D., R.D. Meade, and J.N. Winn, *Photonic Crystals: molding the flow of light*, Princeton University Press: Princeton, 1995.

[4] Shumpert, J.D., T. Ellis, G. Rebeiz, and L.P.B. Katehi, "Microwave and Millimeter-wave Propagation Through Photonic Band-Gap Structures," *1997 IEEE Antennas and Propagation Society (AP-S) International Symposium and URSI Radio Science Meeting*, 13-18 July 1997, Montreal, Quebec, Canada.

[5] Yablonovitch, E. "Inhibited spontaneous emission in solid-state physics and electronics," *Phys. Rev. Lett.*, vol. 58, no. 2, pp. 2059-62, 1987.

[6] Yang, H.Y., "Finite difference analysis of 2-D photonic crystals," *IEEE Trans. Microwave Theory Tech.*, vol. 44, no. 12, pp. 2688-95, 1996.

[7] Yang, H.Y., "Characteristics of guided and leaky waves on multilayer thin-film structures with planar material gratings," *IEEE Trans. Microwave Theory Tech.*, vol. 45, no. 3, pp. 428-35, 1997.

[8] Special issue of the *Journal of the Optical Society of America B* (vol. 10, no. 2, Feb. 1993).

[9] Special issue of the *Journal of Modern Optics* (vol. 41, no. 2, Feb. 1994).

A 1997 IEEE AP-S International Symposium and URSI North American Radio Science Meeting Presentation

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Outline

- Motivation
- Introduction to Photonic Band-Gap Concepts
- Preliminary Results
    - Experimental
    - Theoretical
- Observations
- Future Work

Motivation

Model high-efficiency antennas and circuits

- high-density materials used for substrates
- planar circuits and antennas for high frequency applications

Planar antennas and circuits

<u>Advantages</u>	<u>Disadvantages</u>
conformal	low gain
easily integrated into thin-film circuits	ohmic and dielectric loss (substrate or surface waves)

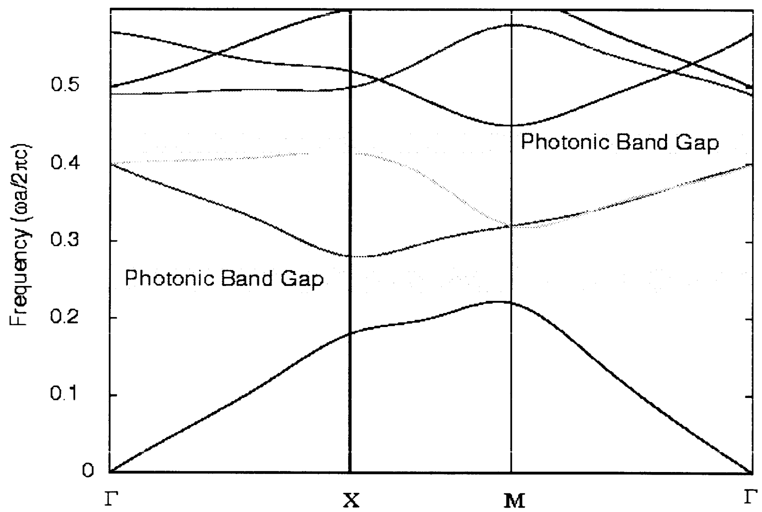
Surface-wave Suppression

How can surface wave losses be eliminated in planar circuits and antennas ?

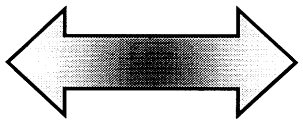
Candidate technologies currently under investigation at the University of Michigan:

micromachined substrates
dielectric lenses
photonic band-gap (PBG) materials

Introduction to Photonic Band-Gaps



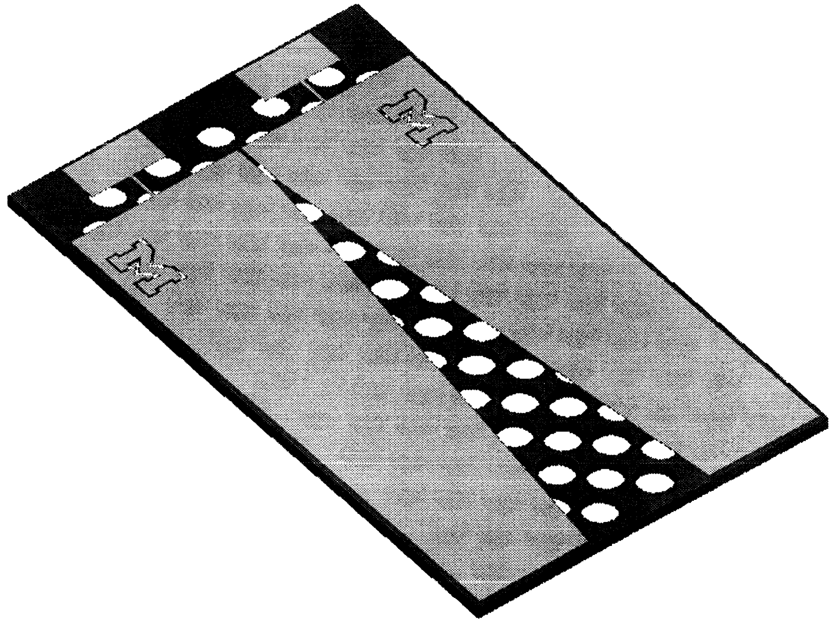
Electromagnetic wave propagation in periodic dielectric material



Electron wave propagation in semi-conductor crystals

Photonic Band-Gap Applications

What are photonic band-gaps good for?



Offer the advantage of changing the physical properties of the substrates used in fabricating planar antennas and circuits

Applications include:

dielectric mirrors, resonant cavities, high Q filters, isolators, dielectric waveguides, couplers, frequency selective surfaces (FSS)

Primary Goals

Develop 2-D model to study substrate characteristics

- Effects of substrate geometry in determining band-gap region
- Effects of metallization on substrate properties

Develop 3-D model to simulate planar antennas and circuits

- Surface wave characterization, radiation pattern, and radiation efficiency
- Band structures for various artificial substrates

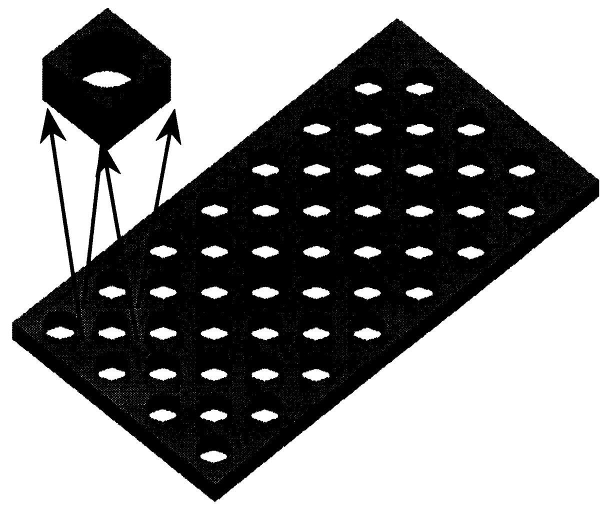
Theoretical Investigation of Artificial Substrates

Moment method analysis

- Full-wave doubly periodic moment method (PMM) solution
- Use equivalent volume (polarization) currents
- Use quasi-Green's function for unit cell of the periodic structure

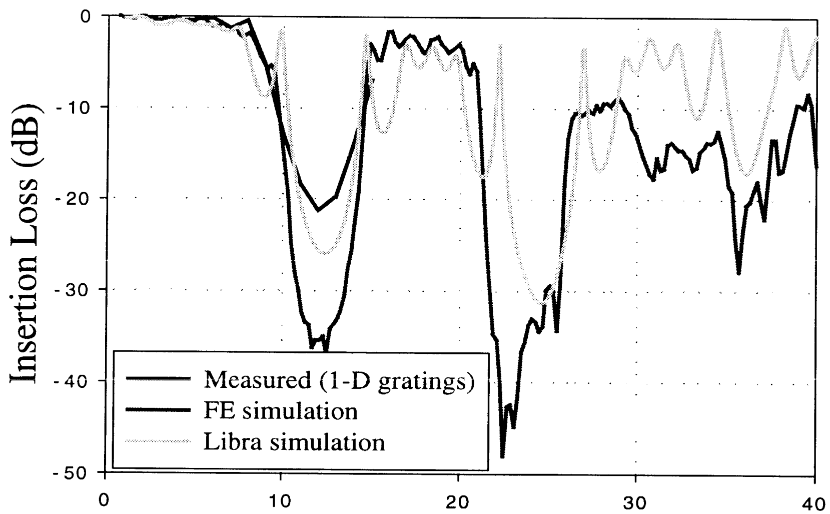
Finite element analysis

- Full 3-D simulation of entire structure

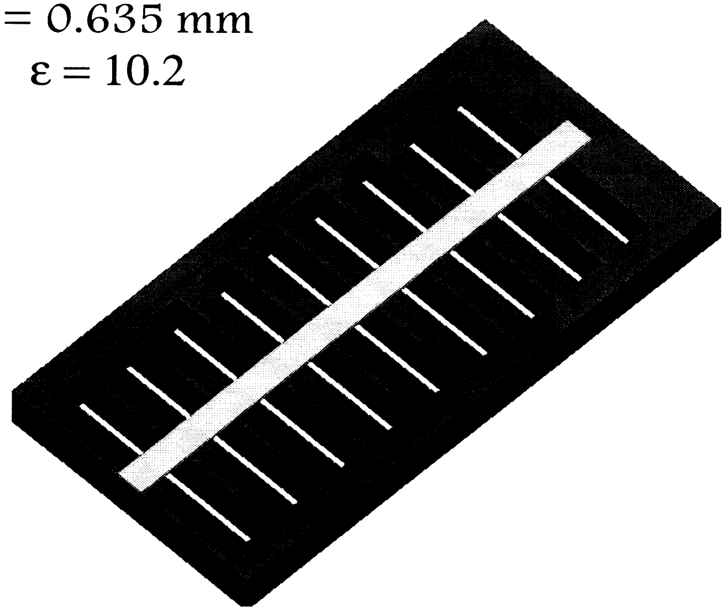


Experimental Investigation of Artificial Substrates

1-D periodic dielectric
grounded slab (microstrip)



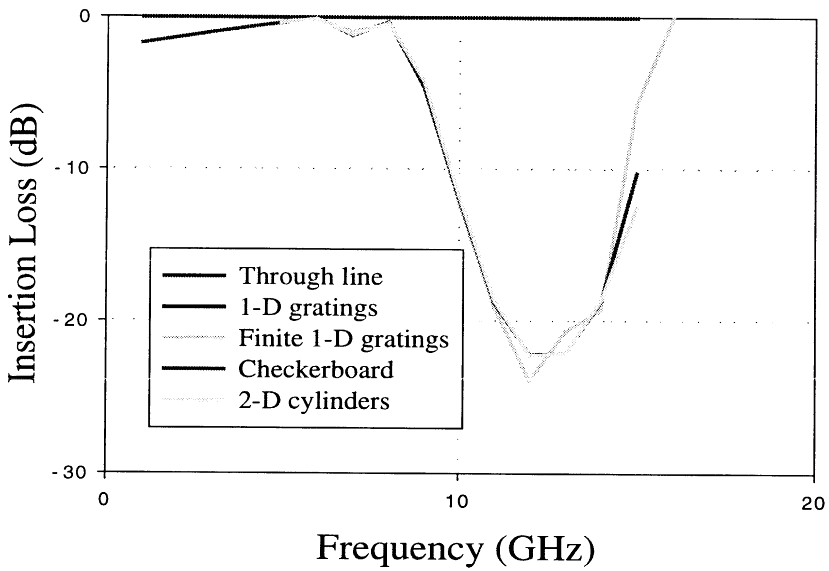
$\Lambda = 6.35$ mm
$h = 0.635$ mm
$\varepsilon = 10.2$

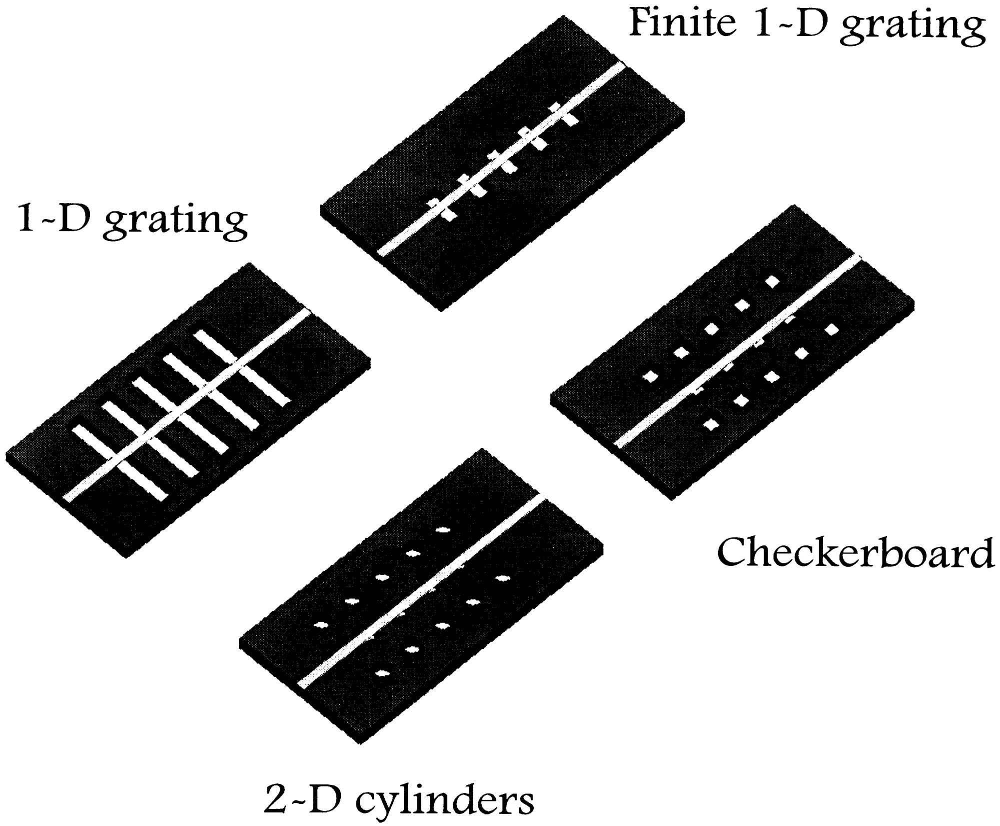


1-D periodic dielectric
grounded slab

Experimental Investigation of Artificial Substrates

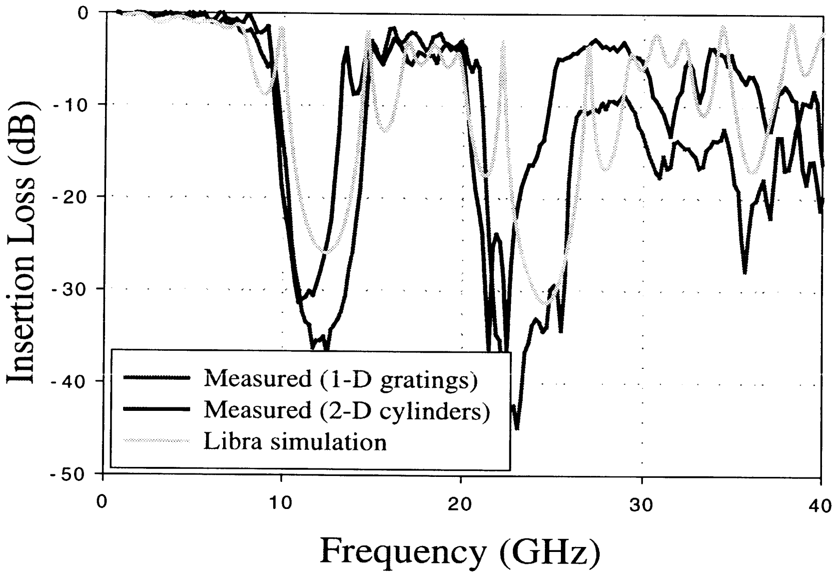
Progression of dielectric removal

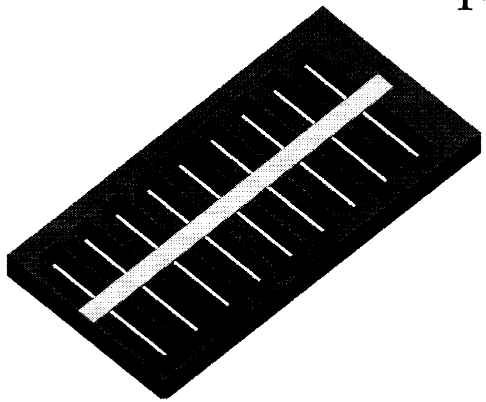




Experimental Investigation of Artificial Substrates

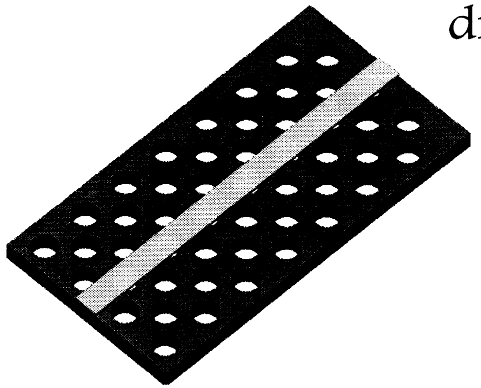
1-D and 2-D periodic dielectric grounded slab (microstrip)





1-D periodic dielectric grounded slab

$\Lambda = 6.35$ mm
$h = 0.635$ mm
$\varepsilon = 10.2$

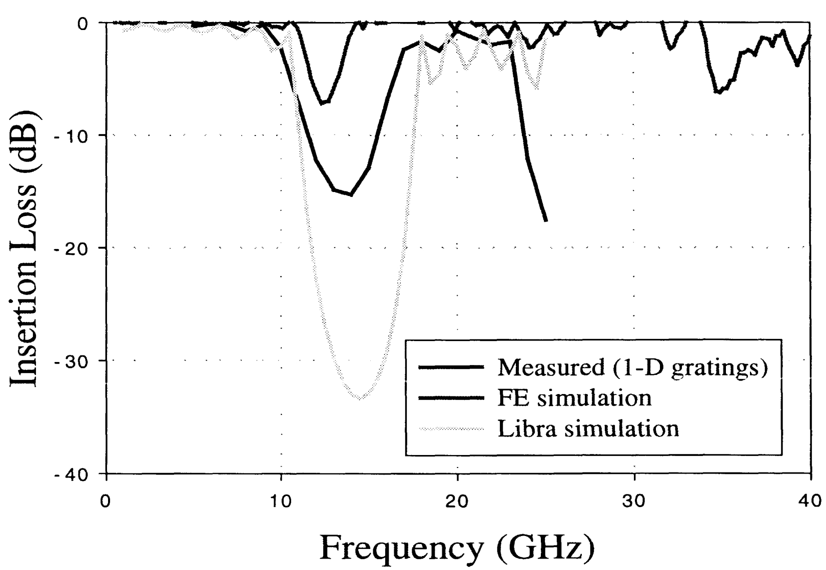


2-D planar periodic dielectric grounded slab

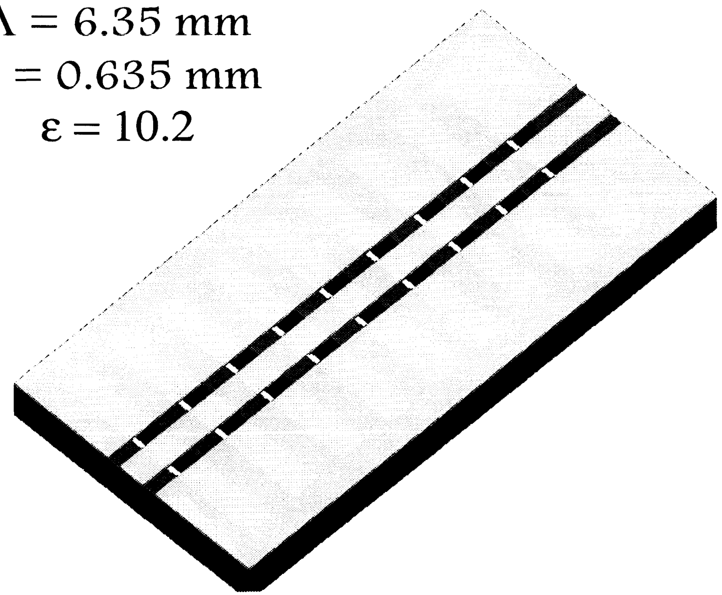
$\Lambda = 6.35$ mm
$h = 0.635$ mm
$a = 4.49$ mm
$r = 1.585$ mm
$\varepsilon = 10.2$

Experimental Investigation of Artificial Substrates

1-D periodic dielectric slab (CPW)



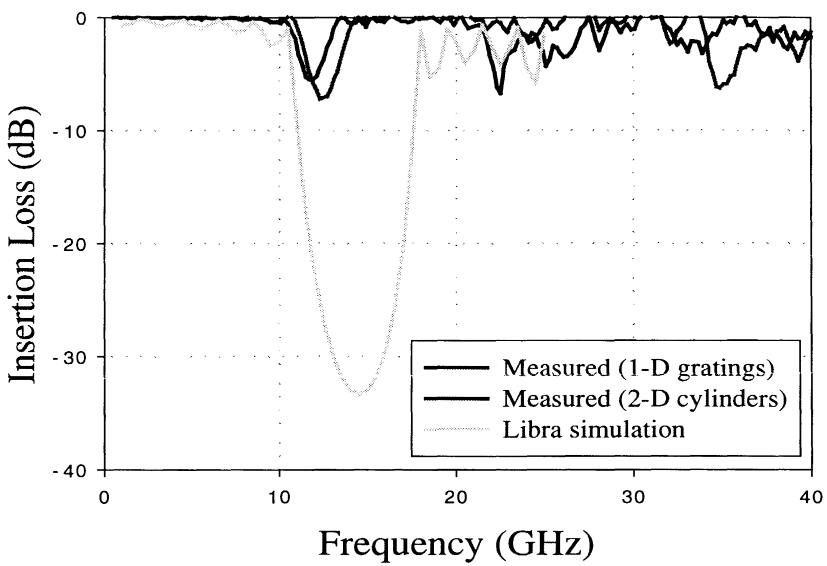
$\Lambda = 6.35$ mm
$h = 0.635$ mm
$\varepsilon = 10.2$

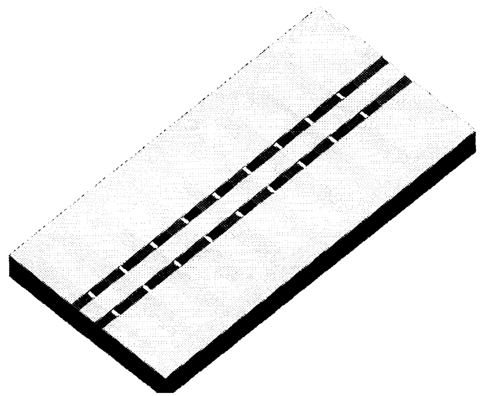


1-D periodic dielectric slab

Experimental Investigation of Artificial Substrates

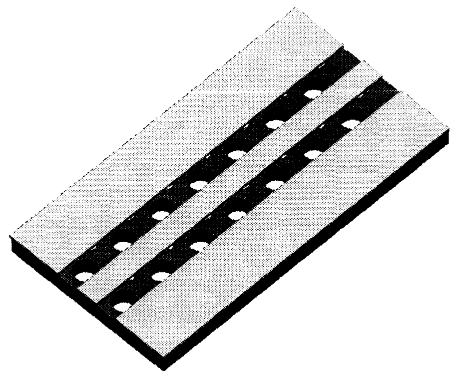
1-D and 2-D periodic dielectric slabs (CPW)





1-D periodic dielectric slab

$\Lambda = 6.35$ mm
h = 0.635 mm
$\varepsilon = 10.2$



2-D planar periodic dielectric slab

$\Lambda = 6.35$ mm
h = 0.635 mm
a = 4.49 mm
r = 1.585 mm
$\varepsilon = 10.2$

Summary

- Preliminary results suggest that microwave and millimeter-wave frequencies can be manipulated by carefully designing and fabricating structures composed of regions of differing dielectric constants

- Candidate technologies currently under investigation for surface-wave suppression: micromachined substrates, dielectric lenses, and photonic band-gap (PBG) materials

- PBGs offer the advantage of changing the physical properties of the substrates used in fabricating planar antennas and circuits

- Model effects of substrate geometry and metallization on substrate properties such as surface-wave formation

Future Work

Computational

- metallize holes / dielectric cylinders
- metallize cover region
- couple problem with printed circuits
- convergence

Experimental

- microstrip and CPW excitation of 2-D crystals
- thin-Si substrate
- surface wave suppression

Suggested Reading

1. Yablonovitch, E., "Inhibited spontaneous emission in solid-state physics and electronics," *Phys. Rev. Lett* ., vol. 58, no. 2, pp. 2059-62, 1987.

Special Issues on Photonic Band Structures

2. Special issue of the *Journal of the Optical Society of America B* (vol 10, no. 2, Feb. 1993).
3. Special issue of the *Journal of Modern Optics* (vol. 41, no. 2, Feb. 1994).

Photonic Crystals (Overview)

4. Joannopoulos, J.D., R.D. Meade, and J.N. Winn, *Photonic crystals: molding the flow of light*, Princeton University Press: Princeton, NJ, 1995.

Planar Antenna on Photonic Crystal Substrates

5. Brown, E.R., C.D. Parker, and E. Yablonovitch, "Radiation properties of a planar antenna on a photonic-crystal substrate," *J. Opt. Soc. Am. B*, vol. 10, no. 2, pp.404-7, 1993.

Numerical analysis

6. Yang, H. Y., "Finite difference analysis of 2-D photonic crystals," *IEEE Trans. Microwave Theory Tech.*, vol. 44, no. 12, pp. 2688-95, 1996.

7. Yang, H. Y., "Characteristics of guided and leaky waves on multilayer thin-film structures with planar material gratings," *IEEE Trans. Microwave Theory Tech.*, vol. 45, no. 3, pp. 428-35, 1997.