Springer Series in Optical Sciences

Volume 187

For further volumes:
http://www.springer.com/series/624

Springer Series in Optical Sciences

The Springer Series in Optical Sciences, under the leadership of Editor-in-Chief William T. Rhodes, Georgia Institute of Technology, USA, provides an expanding selection of research monographs in all major areas of optics: lasers and quantum optics, ultrafast phenomena, optical spectroscopy techniques, optoelectronics, quantum information, information optics, applied laser technology, industrial applications, and other topics of contemporary interest.

With this broad coverage of topics, the series is of use to all research scientists and engineers who need up-to-date reference books.

The editors encourage prospective authors to correspond with them in advance of submitting a manuscript. Submission of manuscripts should be made to the Editor-in-Chief or one of the Editors. See also www.springer.com/series/624

Basudeb Ghosh · Sachendra N. Sinha
M. V. Kartikeyan

Fractal Apertures in Waveguides, Conducting Screens and Cavities

Analysis and Design

Springer

Basudeb Ghosh
Department of Avionics
Indian Institute of Space Science and Technology
Thiruvananthapuram
India

Sachendra N. Sinha
M. V. Kartikeyan
Department of Electronics and Communication Engineering
Indian Institute of Technology Roorkee
Roorkee
India

ISSN 0342-4111 ISSN 1556-1534 (electronic)
ISBN 978-3-319-06534-2 ISBN 978-3-319-06535-9 (eBook)
DOI 10.1007/978-3-319-06535-9
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014938723

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Fractal geometries have widely been used in electromagnetics, specifically, in antennas and frequency selective surfaces (FSS). The self-similarity of fractal geometry gives rise to a multiband response, whereas the space-filling nature of the fractal geometries makes it an efficient element in antenna and FSS unit cell miniaturization. Till date, no effort has been made to study the behavior of these fractal geometries in the aperture coupling problems. Aperture coupling problem is an important boundary value problem in electromagnetics, and has widely been used in waveguide filters and power dividers, slotted ground planes, frequency selective surfaces, and metamaterials. The present work is primarily intended to initiate a study on the characteristics of fractal apertures in waveguides, conducting screens, and cavities.

In order to carry out a unified analysis of these entirely dissimilar problems, the "generalized network formulation for the aperture problems" proposed by Mautz and Harrington has been extended to multiple-aperture geometry. We have considered the problem of coupling between two arbitrary regions coupled together via multiple apertures of arbitrary shape. The two regions are decoupled by the application of equivalence principle and enforcement of boundary conditions over the aperture regions that lead to an operator equation. The operator equation is then reduced to matrix form via the Method of Moments (MoM). The general problem of coupling through apertures is formulated in such a manner that only part of the problem needs to be reformulated for the solution of different problems like fractal diaphragms in a rectangular waveguide, radiation from waveguide-fed fractal apertures, coupling through fractal apertures in a conducting screen, and radiation from cavity-backed fractal apertures. A Galerkin procedure with rooftop and Rao-Wilton-Glisson (RWG) functions has been used for the first three problems, while a hybrid method using Finite Element Method (FEM) and MoM has been used for the cavity-backed fractal aperture problem. MATLAB codes have been developed for the problems and validated with the results available in the literature as well as through simulation on ANSOFT's HFSS.

The use of resonant apertures in the transverse cross-section of rectangular waveguide improves the out-of-band rejection ratio of waveguide filters and also results in more compact and lightweight waveguide filters. The multiple aperture irises further improve the out-of-band rejection due to the formation of rejection band. Till now, some regular geometries have been analyzed in the literature. Due to requirement of multiple aperture iris and compact waveguide filters, we have studied the behavior of fractal apertures in the transverse cross-section of a waveguide. Two types of basis functions have been used in the analysis. In the first case, the rooftop functions are used to model rectangular aperture problem in which the aperture surface is discretized in small rectangular sub-areas. The integrals involving the Green's function are calculated analytically over the rectangular domain. In the second approach, the apertures are discretized in triangular subareas in order to model the arbitrary aperture surface and RWG functions are used as the basis functions. The integrals over triangular domain are calculated numerically using Gaussian quadrature. The frequency responses of several fractal apertures are studied and some novel self-affine fractal geometries are proposed to obtain multiband response. A study has also been carried out to find a relation between the scale factor of the fractal geometry and the frequency response of the waveguide diaphragm. The study has been further extended to analyze the performance of finite periodic arrangement of these fractal apertures in the design of multiband waveguide filters and electromagnetic bandgap structures (EBG).

The problem of electromagnetic coupling between two regions via apertures in infinite screen has widely been used in the design of FSS, antenna arrays, and slotted ground plane. An infinite screen perforated with multiple apertures has a bandpass response when illuminated by a plane wave of varying frequency. The coupling through fractal apertures in an infinite screen has been solved with RWG basis functions. In this case, the integrals involving the free space Green's function suffer from singularity problem. Singularity cancellation method has been used to calculate the integral, which has the advantage of being accurate and, also, the calculation of these integrals over triangular domain can be done with a purely numerical technique. Several self-similar and space-filling fractal geometries are studied and, also, the effect of the variation of angle of incidence on the frequency response of fractal apertures has been investigated. It has been found that the variation of angle of incidence affects the performance of fractal apertures and some additional pass bands arise for inclined incidence. It is found that the fractal apertures support subwavelength transmission of electromagnetic waves and this property is more prominent in the space-filling fractal apertures. The coupling through the fractal apertures in infinite screen has been extended to the case of radiation through waveguide-fed fractal apertures. It has been found that radiation from such fractal apertures improves the antenna input matching and dual-band waveguide radiators can easily be realized.

Cavity-backed aperture antennas are very popular in aerospace applications due to their conformal nature. The cavity-backed aperture antenna satisfies the requirements of being flush mounted as well as lightweight and small size. Also, the use of metallic cavity makes the radiation pattern unidirectional. Another most important advantage of the cavity-backed apertures is that they offer very small mutual coupling between the elements and are useful in the design of phased arrays. Cavity-backed fractal aperture is another field, which could be explored to design small-sized multiband antennas. The problem has been formulated using combined FEM and MoM method. In the combined FEM/MoM method, the electric field inside the cavity is found using FEM and the surface magnetic current over the aperture surface is calculated using MoM. For FEM formulation, the cavity has been discretized into tetrahedral elements and the apertures into triangular elements. The simultaneous equations obtained over the subdomains are added to form the global matrix equation. This procedure gives a partly sparse and a partly dense matrix, which is then solved to find the unknown electric field over the apertures. The radiation characteristics and input characteristics of the antenna are then calculated from the electric field. The performance of cavity-backed fractal apertures with a coaxial probe feeding has been investigated. The numerical results are again validated with simulation results on HFSS. A novel effort has been made to relate the electromagnetic behavior of the fractal aperture with the scale factor of the geometry. It has been found that the location of resonant frequency of the antenna can be changed by changing the scale factor of fractal apertures.

Roorkee, March 2014

Basudeb Ghosh
Sachendra N. Sinha
M. V. Kartikeyan

Acknowledgments

We sincerely thank the authorities of IIT-Roorkee for making it possible to come up with this book. In addition, special thanks are due to all the authors of the original sources of the figures for the use of their work in the book.

Thanks are due to Mr. Gaurav Singh Baghel and Mr. Ravi Dhakad for their help in proof-reading. We sincerely thank the following journals/publications/ publishers of conference proceedings for their kind permission and for the use of their works and for reprint permission (publication details are given in the respective references and the corresponding citations are duly referred in the captions):

- IEEE, USA
- Springer+Business Media B.V.
- The Electromagnetics Academy (PIER)
- John Wiley and Sons
- APSYM 2006 Symposium
- INDICON 2008 Conference

Contents

1 Introduction 1
1.1 Introduction 1
1.2 Fractal Electrodynamics 2
1.2.1 Fractal Geometries 2
1.2.2 Fractal Antenna Elements 5
1.2.3 Fractal Frequency Selective Surfaces and Filters 7
1.2.4 Fractal Electromagnetic Band Gap Structures and High Impedance Surfaces 7
1.3 Aperture Problems in Electromagnetics 8
1.3.1 Apertures in Waveguide Transverse Cross-Section 8
1.3.2 Coupling Through Apertures in an Infinite Conducting Screen 10
1.3.3 Rectangular Waveguide-Fed Aperture Antennas 12
1.3.4 Cavity-Backed Aperture Antenna 12
1.4 Motivation for Present Research 15
1.5 Research Problems 16
1.6 Organization of the Book 16
References 17

2 Method of Moment Formulation of Coupling Through Apertures 27
2.1 Introduction 27
2.2 General Formulation of Aperture Coupling Problem 28
2.2.1 Fractal Diaphragm in Transverse Cross-Section of Rectangular Waveguide 33
2.2.2 Coupling Between Two Half-Spaces Via Fractal Apertures 33
2.2.3 Rectangular Waveguide-Fed Multiple Apertures in Infinite Conducting Screen 34
2.2.4 Radiation from Multiple Apertures Backed by a Cavity 35
2.3 Basis Functions 37
2.3.1 Rooftop Functions 38
2.3.2 RWG Functions 39

2.4 Evaluation of Admittance Matrix Elements. 39
2.4.1 Semi-Infinite Rectangular Waveguide 40
2.4.2 Half-Space Region 51
2.5 Evaluation of Excitation Vector 54
2.5.1 TE_{mn} Incident Mode in the Rectangular Waveguide 54
2.5.2 Plane Wave Incidence 56
2.6 Far-Field Computation 57
2.7 Conclusion 60
References 60

3 Fractal Frequency Selective Diaphragms in Rectangular Waveguide 61
3.1 Introduction 61
3.2 Formulation of the Problem 62
3.3 Computation of Scattering Coefficients 63
3.4 Numerical Results 66
3.4.1 Modified Devil's Staircase Fractal Diaphragm 66
3.4.2 Self-affine Sierpinski Carpet Diaphragm 70
3.4.3 Sierpinski Gasket Diaphragm 72
3.4.4 Hilbert Curve Diaphragm. 79
3.4.5 Plus Shape Fractal Diaphragm 82
3.4.6 Minkowski Fractal Diaphragm 86
3.4.7 Koch Fractal Diaphragm 89
3.5 Experimental Verification. 90
3.6 Finite Periodic Structures Based on Fractal Diaphragms. 90
3.6.1 Dual-Band Waveguide Filter 91
3.6.2 Waveguide Based Electromagnetic Band Gap Structures 92
3.7 Summary 93
References 94

4 Electromagnetic Transmission Through Fractal Apertures in Conducting Screen 95
4.1 Introduction 95
4.2 General Formulation of the Problem 96
4.3 Computation of Transmission Coefficient and Transmission Cross-Section 97
4.3.1 Transmission Coefficient 97
4.3.2 Computation of Transmission Cross-Section. 99
4.4 Validation of Computer Code 100
4.5 Transmission Through Fractal Apertures 104
4.5.1 Sierpinski Gasket Aperture. 104
4.5.2 Koch Fractal Slot 113
4.5.3 Hilbert Curve Aperture 120

4.5.4 Sierpinski Carpet Aperture 123
4.5.5 Minkowski Fractal Aperture 127
4.6 Summary 130
References 131

5 Radiation from Rectangular Waveguide-Fed Fractal Aperture Antennas 133
5.1 Introduction 133
5.2 Formulation of the Problem 133
5.3 Computation of Antenna Parameters 135
5.3.1 Input Reflection Coefficient 135
5.3.2 Gain Pattern 136
5.4 Numerical Results 137
5.4.1 Sierpinski Gasket Aperture Antenna 138
5.4.2 Hilbert Curve Aperture Antenna 143
5.4.3 Plus Shape Fractal Aperture Antenna 146
5.4.4 Devil's Staircase Fractal Aperture Antenna 149
5.4.5 Koch Fractal Aperture Antenna 151
5.4.6 Minkowski Fractal Aperture Antenna 156
5.5 Experimental Verification 156
5.6 Summary 160
References 161

6 Investigations on Cavity-Backed Fractal Aperture Antennas 163
6.1 Introduction 163
6.2 Formulation of the Problem Using FE-BI Method 164
6.2.1 FEM Formulation in the Interior of the Cavity 165
6.2.2 Boundary-Integral Equation Formulation 169
6.3 Numerical Results 172
6.3.1 Cavity-Backed Rectangular Aperture Antenna 172
6.3.2 Sierpinski Carpet Fractal Aperture 174
6.3.3 Sierpinski Gasket Dipole Aperture Antenna 177
6.3.4 Plus Shape Fractal Aperture Antenna 181
6.3.5 Minkowski Fractal Aperture Antenna 184
6.4 Summary 186
References 187

7 Conclusions and Future Work 189
7.1 Conclusions 189
7.2 Future Work 190
Appendix A: Calculation of Integrals Over Triangular Domains 191
Appendix B: Computation of Singular Integrals 193
References 197

Index 199