

The University of Manitoba

FILTERING AND RADIATION CHARACTERISTICS OF
ANNULAR SLOT ARRAY STRUCTURES

By

BAHMAN AZARBAR

A Thesis
Submitted To The Faculty Of Graduate Studies
In Partial Fulfillment Of The Requirements For The
Degree Of Doctor Of Philosophy

DEPARTMENT OF ELECTRICAL ENGINEERING

Winnipeg, Manitoba
Canada

October 1978

FILTERING AND RADIATION CHARACTERISTICS OF
ANNULAR SLOT ARRAY STRUCTURES

BY

BAHMAN AZARBAR

A dissertation submitted to the Faculty of Graduate Studies of
the University of Manitoba in partial fulfillment of the requirements
of the degree of

DOCTOR OF PHILOSOPHY

© 1978

Permission has been granted to the LIBRARY OF THE UNIVER-
SITY OF MANITOBA to lend or sell copies of this dissertation, to
the NATIONAL LIBRARY OF CANADA to microfilm this
dissertation and to lend or sell copies of the film, and UNIVERSITY
MICROFILMS to publish an abstract of this dissertation.

The author reserves other publication rights, and neither the
dissertation nor extensive extracts from it may be printed or other-
wise reproduced without the author's written permission.



To the memory of

MONEER NAGHAVI KAMAL

for all her love and devotion

ABSTRACT

A method is established which gives field solutions inside two radial waveguides coupled by an array of annular slots on the common boundary. The cases of electromagnetic penetration into half space as well as cylindrical cavity regions are also treated. For the half space problem, the thickness of one of the waveguide regions is allowed to approach infinity. Whereas, for the cylindrical cavity case, the radial waveguide is terminated at an appropriate place by a cylindrical short circuit. Since the analysis is based on the response of the system to azimuthal current rings, the appropriate Green's functions for electric current rings are obtained in a similar manner as those of magnetic type. Therefore, the method can be extended to the geometries involving annular or cylindrical type conducting bodies as well as aperture-type geometrical discontinuities.

The solution is obtained by constructing the impulse response of the system and expressing the induced current distribution over the slots and the conducting bodies in terms of a suitable set of basis functions with complex coefficients. These constants are then obtained by an application of the boundary conditions on the discontinuity surfaces. The method is applied to three different geometries, namely, two radial waveguides coupled by an array of annular slots on the common boundary, an annular slot array antenna fed by a radial waveguide and the cavity backed annular slot antenna. Graphical results for selected cases are presented to substantiate the applicability of the models in the design of microwave filtering devices as well as highly directive antenna systems.

It is also shown that, in general, higher order modes excited by the discontinuities can have significant effect on the solution and for a precise evaluation of the fields in the respective regions, their contribution must also be included. A method of generating the desired incident mode or modes is suggested which uses simple vertically oriented arrays of thin probes.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Dr. L. Shafai of the Electrical Engineering Department, University of Manitoba, for his guidance, constant encouragement and constructive criticism, throughout all phases of this work.

The valuable review of the entire manuscript by my wife, Mrs. Elaheh Kamal Azarbar, led to a number of clarifications and other improvements. Her understanding and forbearance throughout the years made this work possible. To Ms. M. Tyler, the author expresses his special gratitude for her cheerful and patient efforts in an excellent typing job and editorial assistance throughout the several drafts of this dissertation.

It is a pleasure to thank Professor E. Bridges for his many helpful suggestions. The author is also indebted to Mr. A. McKay, Electronics Technologist and Mr. A. Symmons, Machining Technologist of the Electrical Engineering Department who have made various contributions in the fabrication process of the antenna model. Drafting facilities provided by Mr. H.H. Weiss of the Central Drafting Office and secretarial assistance by Mrs. L. Ramsay is appreciated.

Thanks are also due to my colleagues, Mr. H. Kunkel for his help in the early stages of the research project and Mr. A. Ittipiboon and Mr. M. Jullian for their assistance in the experimental phase of this work.

The financial support by the National Research Council of Canada in the form of Post-graduate Scholarship and the Operating Grant A7702 and also through the University of Manitoba in the form of University Fellowship is appreciated.

TABLE OF CONTENTS

CHAPTER		PAGE
	ABSTRACT	<i>i</i>
	ACKNOWLEDGEMENTS	<i>iii</i>
	TABLE OF CONTENTS	<i>iv</i>
	LIST OF FIGURES	<i>vii</i>
	LIST OF SYMBOLS	<i>x</i>
I	INTRODUCTION	1
II	STATEMENT OF THE PROBLEM AND LITERATURE SURVEY	6
	2.1 Introduction	6
	2.2 Outline of the Subject Under Investigation	10
III	FIELD SOLUTION FOR RADIAL WAVEGUIDES IN THE PRESENCE OF ANNULAR OR CYLINDRICAL TYPE GEOMETRICAL DISCONTINUITIES	14
	3.1 Introduction	14
	3.2 Problem Formulation and Solution	18
	3.2.1 Construction of the appropriate Green's functions, magnetic ring	18
	3.2.2 Electric ring	24
	3.3 Application to the Problem of Two Coupled Radial Waveguides	27
	3.3.1 Formulation of the problem of two coupled radial waveguides	29
	3.3.2 Expressions for the total, transmitted and the coupled power	41
	3.4 Equivalent Admittance of an Annular Slot	43
	3.4.1 Effects of the higher order modes on the admittance and the field of an annular slot	43
	3.5 Filtering Characteristics of Two Coupled Radial Waveguides	48
IV	FIELD SOLUTION FOR ANNULAR SLOT ARRAYS FED BY RADIAL WAVEGUIDES	55
	4.1 Introduction	55

CHAPTER	PAGE
4.2 Problem Formulation and Solution	58
4.2.1 Construction of the appropriate Green's functions, magnetic ring	58
4.2.2 Electric ring	64
4.3 A Note on the Branch Cuts of the Function $\gamma = (\alpha^2 - k_0^2)^{\frac{1}{2}}$	66
4.4 Formulation of the Problem of a Waveguide- Fed Annular Slot Array Antenna	68
4.5 Evaluation of Infinite Integrals	74
4.6 Radiation Field	78
4.6.1 Expression for the radiated power	81
4.7 Effects of the Higher Order Modes on the Admittance and the Field of a Waveguide- Fed Annular Slot Antenna	82
4.8 Amplitude and Phase Variation of an Isolated Annular Slot as a Function of its Average Radius	88
4.8.1 Amplitude and phase variation of two coupled slots	91
4.9 Radiation Characteristics of Annular Slot Array Antennas	95
V FIELD SOLUTION FOR CAVITY BACKED ANNULAR SLOT ARRAYS	105
5.1 Introduction	105
5.2 Problem Formulation and Solution	107
5.2.1 Construction of the appropriate Green's functions, magnetic ring	107
5.2.2 Electric ring	112
5.3 Formulation of the Problem of a Cavity Backed Annular Slot Array Antenna	115
5.3.1 Expression for the total power	117
5.4 Radiation Characteristics of Cavity Backed Annular Slot Arrays	120
5.5 Excitation of Radial Waveguides	125
5.5.1 Introduction	125
5.5.2 Method of excitation of a TM_{00} radial mode	127
5.5.3 Method of excitation of a TM_{01} radial mode	130
5.6 Effects of a Finite Ground Plane on the Radiation Field	134
5.7 Experimental Results	135

CHAPTER	PAGE
VI DISCUSSION AND CONCLUSION	146
6.1 Suggestions for Future Research	151
APPENDIX A	153
APPENDIX B	155
APPENDIX C	159
APPENDIX D	162
APPENDIX E	164
APPENDIX F	166
APPENDIX G	167
REFERENCES	169

LIST OF FIGURES

FIGURE		PAGE
1.1	Basic radiating element	3
3.1	Current ring in a radial waveguide (impulse response)	16
3.2	Typical two coupled radial waveguides of infinite extent	28
3.3a	Effect of higher order modes on the equivalent conductance of the slot. Ratio of the edges = 2.36, $k_{0a} = k_{0b} = 0.49$, $\epsilon_{r1} = \epsilon_{r2} = 1.00$, k_0 is free space propagation constant	45
3.3b	Effect of higher order modes on the equivalent susceptance of the slot	46
3.4a	Amplitude distribution over the slot, $k_0\delta = 2.72$, $k_0\rho = 3.36$, $k_{0a} = k_{0b} = 0.49$, $\epsilon_{r1} = \epsilon_{r2} = 1.00$	47
3.4b	Phase distribution over the slot	47
3.5	Filter characteristic of a single slot, TM_{00} exciting mode. $\epsilon_{r1} = 2.60$, $\epsilon_{r2} = 5.20$, $k_{0a} = 0.34$, $k_{0b} = 0.04$, $k_0\delta = 0.05$, $k_0\rho = 8.39$. All dimensions are at f_0 .	52
3.6	Filter characteristics of four slots, TM_{00} exciting mode. $\epsilon_{r1} = 2.60$, $\epsilon_{r2} = 5.20$, $k_{0a} = k_{0b} = 0.34$, $k_0\delta = 0.08$, $k_{0\rho1} = 10.08$, $k_{0x} = 4.05$	53
3.7	Filtering response of the same geometry as in figure 3.6, TM_{01} mode of operation. The dotted curve is due to a 4% increase in slot spacing k_{0x} .	54
4.1	Typical radial waveguide fed annular slot array antenna of infinite extent	57
4.2a	A delta-function generated annular slit on an infinite ground plane	59
4.2b	Equivalent problem to figure 4.2a	59
4.3	Branch cuts for $\gamma = (\alpha^2 - k_0^2)^{\frac{1}{2}}$	69
4.4a	Comparison of the conductance term of a radial waveguide fed annular slot against that of a coaxial fed slot of the same aperture size. τ is the ratio of the edges of the slot, $k_{0a} = 0.49$,	85

FIGURE		PAGE
	$\epsilon_r = 1.00$, k_o is free space propagation constant and Y_o is the characteristic admittance of a coaxial waveguide	
4.4b	Comparison of the susceptance terms	85
4.5a	Effect of higher order modes of the feeding guide on the equivalent conductance of the slot. $\tau = 2.36$, $k_o a = 0.49$, $\epsilon_{r1} = 1.00$	86
4.5b	Effect of higher order modes of the feeding guide on the equivalent susceptance of the slot	86
4.6a	Amplitude distribution over the slot, $k_o \delta = 2.72$, $k_o \rho = 3.36$, $k_o a = 0.49$, $\epsilon_r = 1.00$	87
4.6b	Phase distribution over the slot	87
4.7	Phase variation of the slot field as a function of its average radius. $k_o \delta = 0.05$, $k_o a = 0.21$, TM_{01} exciting mode.	89
4.8	Weighted amplitude variation of the slot field as a function of its average radius	90
4.9	Phase variation of the slot field of two coupled annular slots as a function of their average radii. $k_o \delta = 0.05$, $k_o a = 0.21$, $k_o x = 1.57$, $\epsilon_r = 2.50$, TM_{01} exciting mode	93
4.10	Weighted amplitude variation of the slot field of two coupled annular slots as a function of their average radii	94
4.11	Radiation pattern of an annular slot array, TM_{00} excitation	96
4.12/a,b	Radiation patterns of an annular slot array, TM_{01} exciting mode, cross-polarization at $\phi = 45^\circ$	99- 100
4.13/a,b	Radiation patterns of an annular slot array, TM_{01} exciting mode, cross-polarization at $\phi = 45^\circ$	101- 102
4.14/a,b	Radiation patterns of an annular slot array, TM_{01} exciting mode, cross-polarization at $\phi = 45^\circ$	103- 104
5.1	Typical cavity-backed annular slot array antenna	106
5.2	Current ring in a cylindrical cavity (impulse response)	108
5.3	Array amplitude distribution. $\epsilon_r = 2.32$, $k_o \delta = 0.30$, $k_o \rho_1 = 5.81$, $k_o x = 4.19$, $k_o a = 0.33$, $(k_o c - k_o \rho_N) = 0.82$, TM_{01} exciting mode	119

FIGURE		PAGE
5.4	Array phase distribution	121
5.5	Radiation patterns of a cavity-backed annular slot array, cross-polarization at $\phi = 45^\circ$, TM_{01} exciting mode	126
5.6	Coaxial line probe at the center of a radial waveguide	128
5.7	Two symmetrically oriented identical probes with a 180° phase difference	131
5.8	Cavity-backed annular slot array antenna and the feed system, TM_{01} excitation	139
5.9	Geometry of the antenna and the feed system	140
5.10	Feed terminals, conducting flange and the mounting fixture.	141
5.11	Assembled annular slot array antenna with the conducting flange	142
5.12	Experimental set-up for pattern measurements	143
5.13	E and H plane radiation patterns of a cavity-backed annular slot antenna. ——— measured, -0-0-0- calculated.	144
5.14	Measured E and H plane radiation patterns of the antenna system with the conducting flange.	145
5.15	Feed assembly used for gain and reflection measurements.	145a
5.16	Magnitude of the reflection coefficient at the feeding arm as a function of frequency.	145c
5.17	Effects of a Slide - Screw tuner on the reflection coefficient.	145d

LIST OF SYMBOLS

Unless otherwise stated, the symbols most commonly used in this thesis have the following meaning:

GREEK ALPHABET:

ϵ	Dielectric constant of a medium.
ϵ_0	Dielectric constant of free space.
μ_0	Permeability of free space.
(ρ, ϕ, z) , (ρ', ϕ', z')	Cylindrical coordinate variables, prime denotes source coordinates.
(r, ϕ, θ)	Spherical coordinate variables.
ρ_i	Average radius of the i th slot.
η_0	Intrinsic wave impedance of free space.
τ	Ratio of the radii of the edges of an annular slot.
λ	Intrinsic wavelength of a region.
λ_0	Free space wavelength.
(ρ_s, ϕ_s)	Coordinates of the feeding probe.
ϵ_r	Relative dielectric constant of a medium with respect to free space.
δ_m	Width of the m th slot.
$\hat{\rho}, \hat{\phi}, \hat{\theta}$	Unit coordinate vectors of the respective variables.
ϵ_n	Neumann constant.
ω	Angular frequency.
ψ^e, ψ^h	Green's functions or wave functions of TM and TE types, respectively.
Φ_n^e, Φ_n^h	Angular dependent part of the n th mode functions of TM and TE types, respectively.

GREEK ALPHABET:

ψ_a^e, ψ_a^h	Auxiliary Green's functions of TM and TE types, respectively.
$\delta(\cdot)$	Delta function.
$\psi_{pq}^e \text{ inc}$	Incident pq mode of TM type.
ρ_m^+, ρ_m^-	Radii of the outer and the inner edges of the mth annular slot.
$\bar{\psi}^e, \bar{\psi}^h$	Hankel transforms of ψ^e and ψ^h , respectively.
γ	Complex propagation constant in the z direction for the spacial frequency domain.
α	Complex variable of the spacial frequency domain.

LATIN ALPHABET:

a, b	Height of radial waveguides.
a_n, b_n	Fourier coefficients in the expansions of the angular dependent part of the current rings and the aperture fields.
c	Radius of a cylindrical cavity.
$C_n^{J,H,N}(\alpha\rho')$	Integrals of the respective Bessel functions with respect to ρ' .
dB, db	Decibel.
E_{in}	Electric field strength of the nth mode over the ith cell.
E_a, H_a, J_a	Auxiliary fields and their source.
$H_n^{(2)}(\cdot), H_n^{(2)\prime}(\cdot)$	Second kind Hankel function of order n and its derivative.
$ H _n(\cdot)$	Struve function of order n.
I^e, I^h	Infinite integrals associated with half-space Green's functions of TM and TE types, respectively.
$I_m(\cdot)$	Imaginary part of a complex number.

LATIN ALPHABET:

$J_n(\cdot), J_n'(\cdot)$	Bessel function of order n and its derivative.
J, J_m	Electric and magnetic current densities, respectively.
$k_{\rho m}$	Radial propagation constant of the m th mode.
k	Wave number of a region.
k_0	Free space wave number.
$\ell_n(\cdot)$	Natural logarithm.
$P_i(\rho' - \rho'_i)$	Unit pulse function of the i th cell.
$R_n(\rho')$	Radial dependent part of the aperture electric field of the n th mode.
$\text{Re}(\cdot)$	Real part of a complex number.
S_1, S_2	Arbitrary cylindrical surfaces in regions I and II, respectively.
S'	Source plane.
TEM	Transverse electromagnetic field to z axis.
TE(h)	Transverse electric to z (h waves).
TM(e)	Transverse magnetic to z (e waves).
TM_{mn}	Transverse magnetic field of the (mn) th mode.
$U_{mn}^e, V_{mn}^e, U_{mn}^h$	Coefficients of the (mn) th mode of radial waveguide and cavity Green's functions of TM and TE types, respectively for $\rho > \rho'$
u_{mn}^e, u_{mn}^h	Coefficients of the (mn) th mode of radial waveguide and cavity Green's functions of TM and TE types, respectively for $\rho < \rho'$
$U_n^e(\cdot), U_n^h(\cdot)$	Coefficients of the n th mode of the half-space Green's functions of TM and TE types, respectively.

CHAPTER I

INTRODUCTION

Telecommunication technology has reached the state of maturity which allows reliable contact between terrestrial points to be established within seconds. As a prime contributor to this achievement, communication satellites have been used for a large number of diverse services. The early recognition of their potential use in world-wide communication prompted a rapid growth of international and military satellite communication systems, an industry which is barely ten years old.

One of the significant elements underlying this growth was the prospect of achieving band-widths exceeding those previously available for intercontinental communications. The exploitation of the wide band-widths now easily available in the use of satellites and the ever increasing demand for higher frequencies requires solution to a series of technical problems in the communication links. As an inherent part of these links, earth station and spacecraft antennas must also conform to the specific needs as they arise. This is why satellite antennas have developed from low-gain, omnidirectional antennas to multifrequency multi-function antenna systems now in use [1,2].

Still higher frequencies are under active consideration, not only because of spectrum crowding at the lower frequency bands, but because of the desire to accommodate higher data rates than are now being sent commercially. So far, there have been a number of different design approaches conforming to satellite stabilization considerations which have been tested for their performance in actual missions [1-9].

Generally speaking, the optimum goal in designing any satellite antenna is to attain a pre-specified high gain radiation pattern by using a low profile antenna with the least complex feed system, with low weight and volume occupied by the antenna assembly, ease of fabrication and, most important of all, lower manufacturing cost factor. The last two goals are becoming more important as the frequency spectrum is broadened constantly and satellite communication is exploited commercially.

The purpose of the present work is to study a new class of low profile radiating element for use in high frequency telecommunication systems. The structure may be used as the basic block in formation of high frequency filtering devices as well as low profile antenna systems for applications in aircrafts, spacecrafts and low cost earth stations. Due to the structural simplicity of the radiating element it looks quite promising for use at high frequencies and the production cost seems to be much lower than conventional types presently in use.

The basic element is essentially a slotted radial waveguide. It is formed by an array of co-centered electrically narrow annular slots etched on one side of a dielectric substrate which is sandwiched by two ground planes, figure 1. For applications as an antenna, depending on the excitation of the slots, the structure is capable of producing radiation patterns with the main lobe in the direction of the z-axis (end fire) or a doughnut type radiation field with a null in that direction (broad-side). Terminology is borrowed from conventional arrays by viewing the antenna as a compressed version of a stack of circular loop radiators.

An important consideration for antenna systems covering large angular regions lies in their polarization state over the coverage zone.

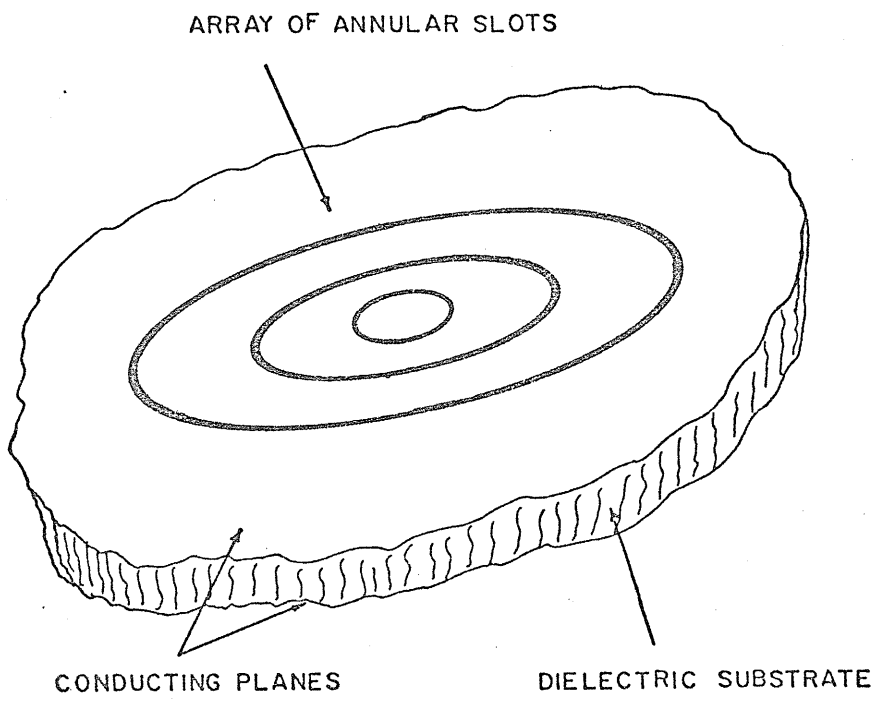


Figure 1.1: Basic radiating element.