

STUDIES ON OPTICAL WAVEGUIDES USED IN FIBER AND INTEGRATED OPTIC DEVICES

A thesis submitted in fulfilment of
the requirements of the degree of

DOCTOR OF PHILOSOPHY

by

M. RAJARAM SHENOY



DEPARTMENT OF PHYSICS

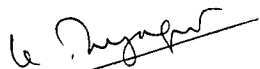
INDIAN INSTITUTE OF TECHNOLOGY, DELHI
(INDIA)

FEBRUARY, 1987

to my mother and father

C E R T I F I C A T E

This is to certify that this thesis entitled STUDIES ON OPTICAL WAVEGUIDES USED IN FIBER AND INTEGRATED OPTIC DEVICES, being submitted by M. Rajaram Shenoy, to the Indian Institute of Technology, Delhi, is a record of bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements, which to our knowledge, have reached the requisite standard for the submission of this thesis. The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.



(K. THYAGARAJAN)
Assistant Professor
Department of Physics
Indian Institute of
Technology Delhi
New Delhi-110016
INDIA



(ARUN KUMAR)
Assistant Professor
Department of Physics
Indian Institute of
Technology Delhi
New Delhi-110016
INDIA

ABSTRACT

Recent advances in material fabrication and characterisation techniques, analytic tools and computational power have greatly enhanced the scope of fiber and integrated optics. Rapid progress in low loss high bandwidth optical fiber communication, as well as the increasing interest in fiber and integrated optical devices for use in non-communication applications such as signal processing and fiber sensors, has been the impetus for the design and development of a wide variety of fiber and integrated optical waveguides. The present thesis is devoted to the study of some of the waveguides and waveguiding configurations that occur in various fiber and integrated optical devices; a major portion of the thesis deals with the most important theoretical aspects of these waveguides relevant to the design of devices.

In the first part, a general and efficient matrix technique for planar waveguides with a few modes and arbitrary index profiles is established. The method involves straightforward multiplication of 2×2 matrices and does not require the solution of any transcendental/differential equation. In particular, the applicability and usefulness of the method to determine the propagation constant, field profile, and leakage/absorption losses have been demonstrated. Next, we have presented an analysis, under the

weakly guiding approximation, describing the propagation and loss in bent waveguides characterised by a separable profile, which may be graded in the transverse direction. We have then shown how the matrix method can be used to calculate accurately the bending loss in such waveguides. We have also suggested a novel refractive index profile for which the bending losses can be made extremely small. Further, the applicability of the matrix technique to one dimensional Schrodinger equation, and hence to quantum well structures, has been demonstrated. The method allows straightforward estimation of bound-state and quasi-bound state energy eigenvalues (and lifetimes of the latter) for arbitrary one dimensional potentials. Lastly, the matrix method has been extended to the analysis of optical fibres characterised by cylindrically symmetric refractive index profiles. As specific examples, three different fibres, namely, a single-clad fiber, a coaxial fiber, and a double-clad fiber are considered. Attempt in all the above examples has been to show the applicability of the matrix approach and that it is capable of yielding very accurate results. Apart from its simplicity and versatility, the most important advantage of the method is its ability to calculate the loss coefficient of a given mode in a leaky or absorbing waveguide, without involving any additional complexities unlike other numerical techniques.

In the second part of the thesis, a study on some of the birefringent waveguides has been presented. In particular, we have applied a perturbation method to determine the propagation characteristics of a rectangular-core anisotropic waveguide characterised by a diagonal dielectric constant tensor. The method has been then extended to determine the polarization characteristics of elliptic-core fibres with stress induced anisotropy; the method simultaneously takes into account both geometrical and stress birefringence. We have shown that neglecting the geometrical birefringence, even under the weakly guiding approximation, can lead to significant errors in the calculation of polarization-mode-dispersion (PMD) and the wavelength of zero PMD. Finally, we have presented an experimental technique for the measurement of propagation constant, and hence modal birefringence of highly birefringent single-mode fibers using prism (output) coupling. Experimental details and results of birefringence measurements on an elliptic-core fiber has been presented.

ACKNOWLEDGEMENTS

It is my great good fortune that I have been a part of the Optical Waveguide Group (OWG) during the course of this work, and I am grateful to the leadership of Professor A.K. Ghatak, whose active interest in the personal and academic welfare of all in his charge has fostered an atmosphere of friendship and close cooperation in the OWG. Professor Ghatak has also been directly involved in my research work, and I owe my sincere thanks to him for his guidance and keen interest in the progress of this work. I am also indebted to Professor I.C. Goyal for his constant encouragement and many fruitful discussions during all phases of this work.

I wish to express my deep sense of gratitude to my research supervisors, Dr. K. Thyagarajan and Dr. Arun Kumar, who have devoted an incalculable amount of time for the successful completion of this thesis; they were always ready to discuss and offer advice on all aspects of my work.

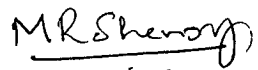
I gratefully acknowledge many useful and often stimulating discussions with Dr.(s) Ajit Kumar, Anurag Sharma, B.D. Gupta, B.P. Pal, A.D. Sharma, (Mrs.) E.K. Sharma and G. Umesh. Yet it is their friendship and ready interest in my opinions and aspirations, both in and out of work hours, that I have appreciated most.

Many of the other members of the OWG have in their own way, smoothed my passage through the last four and a half years. In particular, I should thank my friends Ashok Kaul, Iqbal Hossain, Prasanna Mishra, Ramanand Tewari, Ravendra

Varshney, Somenath Sarkar and Subrahmanyam, for I have enjoyed working in their company. My thanks are also due to my colleagues Ramadas Pillai and Verghese Paulose for their cooperation and willingness to help in all aspects of my work. Also, I must include a special note of appreciation to my younger colleagues Jacintha Kompella, Ravindra Sinha, Supriya Diggavi, Swagatha Banerjee, Umesh Das, Vineeta Gupta, Vishnupriye and Vrinda Kalia for creating a very friendly and happy working atmosphere; I have learnt many things from them.

The encouragement of my brothers and sisters has undoubtedly allowed me to enjoy my years of study to the full, and I am indeed grateful to them.

Finally, I wish to thank Mrs. Lata Mathur for neatly typing the manuscript.


(M. R. SHENOY)

C O N T E N T S

Abstract	iii
Acknowledgements	vi
1. INTRODUCTION	1
2. THE MATRIX METHOD : DEVELOPMENT	14
2.1 Introduction	14
2.2 A planar leaky structure	15
2.3 The matrix method	24
2.4 Summary	33
3. MATRIX METHOD : APPLICATION TO PLANAR OPTICAL WAVEGUIDE STRUCTURES	34
3.1 Introduction	34
3.2 Inhomogeneous planar waveguide	34
3.3 Planar directional coupler	38
3.4 Absorbing structures	42
3.5 Summary	44
4. CALCULATION OF BENDING LOSS IN OPTICAL WAVEGUIDES CHARACTERISED BY A SEPARABLE PROFILE	45
4.1 Introduction	45
4.2 Theory	46
4.3 Numerical results	52
4.4 A novel profile for small bend loss	57
4.5 Summary	58
5. SOLUTION OF ONE DIMENSIONAL SCRODINGER EQUATION USING THE MATRIX APPROACH : APPLICATION TO QUANTUM WELL STRUCTURES	59
5.1 Introduction	59
5.2 Theory	61
5.3 Application to quantum well structures	66
5.4 Summary	73

6.	ANALYSIS OF OPTICAL FIBERS CHARACTERISED BY A CYLINDRICALLY SYMMETRIC REFRACTIVE INDEX PROFILE USING THE MATRIX APPROACH	74
6.1	Introduction	74
6.2	Method	75
6.3	Applications	80
6.4	Summary	90
7.	A SIMPLE PERTURBATION APPROACH FOR THE ANALYSIS OF ANISOTROPIC RECTANGULAR-CORE WAVEGUIDES	93
7.1	Introduction	93
7.2	Method	94
7.3	Results and discussions	102
7.4	Summary	106
8.	POLARIZATION CHARACTERISTICS OF ELLIPTIC-CORE FIBERS WITH STRESS INDUCED ANISOTROPY	107
8.1	Introduction	107
8.2	Method	109
8.3	Results and discussions	113
8.4	Summary	122
9.	PRISM COUPLING TECHNIQUE : MEASUREMENT OF PROPAGATION CONSTANT AND BEAT LENGTH IN SINGLE - MODE FIBERS	123
9.1	Introduction	123
9.2	Method	124
9.3	Experiment and results	126
9.4	Summary	136

Appendices

A	Propagation of a Gaussian beam undergoing frustrated total internal reflection	137
A.1	Introduction	137
A.2	Analysis	140
A.3	Discussion	147
A.4	Summary	150
B	Derivation of Eq. (2.25).	151

C	Computation procedure for using the matrix method..	156
D	A typical computer program for the analysis of a step-index optical fiber using the matrix method	159
	References	163
	Reprints of publications	
	Biodata	