# Chapter 1

# Introduction

## 1.1 Integrated Optics

In the late 1960's the concept of Integrated Optics emerged to describe circuits in which the signals that undergo processing and transmission were optical beams rather than electrical currents [1, 2]. Integrated optics is primarily based on the fact that light beams can propagate through and can be contained by very thin layers (films) of transparent materials. By combining such layers and shaping them into appropriate configurations, integrated optics technology has realized a large variety of components which can perform a wide range of operations on optical waves. Thus, light can be guided, modulated, deflected, filtered, radiated into space, or by using laser action, it can be generated within thin-film structure. Two important technical developments gave impetus to this new technology, these are the development of the laser as a source of light that can be manipulated to carry information and the development of the optical fiber as a viable low-loss transmission medium.

Integrated optics gave rise to a new generation of opto-electronic systems in which the familiar wires and cables are replaced by light guiding optical fibers, and conventional integrated circuits are replaced by optical integrated circuits (OIC). Some advantages of integrated optic systems are reduced weight, increased bandwidth or multiplexing capability, resistance to electromagnetic interference and low loss signal transmission. When the basic components: source, waveguide and detector are all integrated on a single substrate, we have a monolithic OIC. Compound semiconductors such as gallium arsenide ($GaAs$) and indium phosphide ($InP$) are the candidate substrates for this type of IC. When the components are made of different materials, we have a hybrid OIC. For example, the source and detector are made of compound semiconductors such as silicon (Si) and the waveguide is made of dielectric materials such as lithium niobate ($LiNbO_3$) or silica ($SiO_2$).

## 1.2 Optical Waveguides

An optical waveguide is a device which can confine light energy and transport it from one region of space to another with low power loss. A well-known and important example of an optical waveguide is the optical fiber which is a cylindrical waveguide. Usually, total-internal-reflection (TIR) phenomenon is utilized to design such an arrangement. Another example is the dielectric slab waveguide which has a middle layer of high refractive index surrounded by layers of lower refractive indices on both sides. Thus, electromagnetic energy can be trapped inside the high index layer (core) by TIR phenomenon on both sides of the core and can be transported over a long distance. These waveguides could also have a multi-layer structure with more than three layers including metallic layers. The refractive index profile may be uniform (step-index) or continuously varying (graded-index) in each layer.

## 1.3 Waveguide Gratings

Periodic patterns (i.e. gratings) fabricated in optical waveguide structures are one of the most important elements of OIC. They can be used as passive components (e.g. couplers, deflectors, reflectors, wavelength filters, and mode converters), and they have many applications to functional devices for optical wave control. The operation of devices based on gratings depends on electromagnetic wave coupling through phase matching of different propagating modes by the grating region. Figure 1.1 shows a waveguide grating structure, with grating period $T$ and height $h$. This structure is typically composed of hundreds or thousands of periods. Each discontinuity or period causes a small reflection of the field and the total reflected field is the phasor sum of individual reflections. The grating parameters $T$, $h_g$ and total number of grating periods affect the power reflection and transmission spectra of the structure.

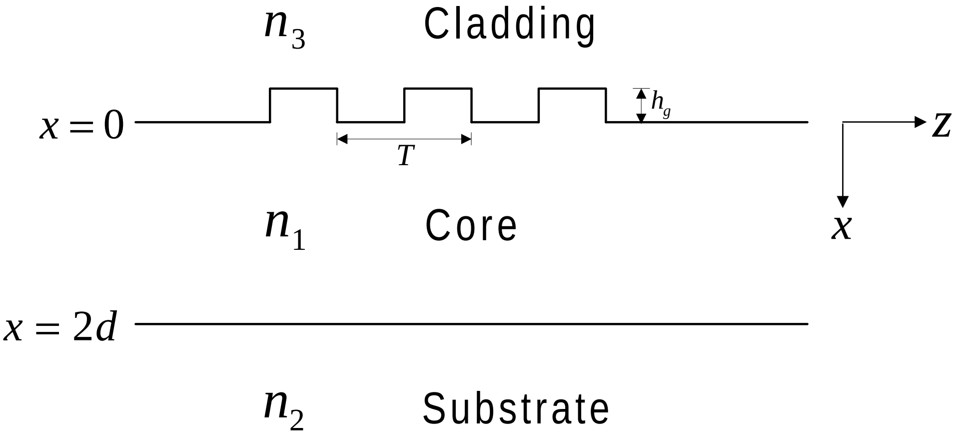

Figure 1.1: Waveguide Grating Structure

## 1.4 Metal-Clad Waveguide

The basic unit that connects the various components of the optical circuits such as sources, detectors, modulators, etc. is the optical waveguide. The optical waveguide performs the function of the metallic strip in electronic circuits, and a rigorous understanding of the operation of the waveguide is essential to the understanding of the operation of other optical circuit components. In addition to this, the use of metals, as well as dielectrics, in the fabrication of optical waveguides offers novel applications that depend on the way different modes and polarizations behave in the presence of metals, in particular on the influence of the metals on the absorption loss of the different modes and polarizations. Early investigations of the effect of metallic layers on the propagation losses in planar film waveguides are reported in the references [3, 4, 5, 6, 7, 8].

Metal-clad waveguides are important in integrated optics because of the variety of applications they offer. Some of the important devices which can be potentially configured around such metal-clad waveguides are photodetectors, modulators, switches, polarization selectors and wavelength filters [9, 10, 11]. In these applications it is important to determine the absorption loss of TE and TM waves. The features of interest are the loss dependence on mode order and the differential TE-TM mode attenuation [12, 13, 14, 15, 16, 17]. A typical three-layer metal-clad waveguide is shown in figure 1.2. In this structure TM modes are more lossy than TE modes [3, 4].

In recent years there has been interest in four-layer metal-clad waveguides in which a buffer layer is introduced between the metal and core layers. A typical four-layer metal-clad waveguide with buffer is shown in figure 1.3. The extinction ratio between the TE and TM modes for either a TE-pass or a TM-pass configuration can be greatly enhanced through appropriate combination of buffer layer and metal layer thicknesses. Some experimental results concerning the role of an intermediate dielectric buffer layer between the waveguide core and its metal cladding are available in the literature. For example, introduction of a low-index buffer layer has been shown to lead to enhanced attenuation of the TM modes for a certain critical buffer layer thickness [18, 19, 20, 21]. Similarly it has been shown that a buffer layer of relatively high refractive index results in causing the TE mode to be more lossy than the TM mode [21, 22, 23].

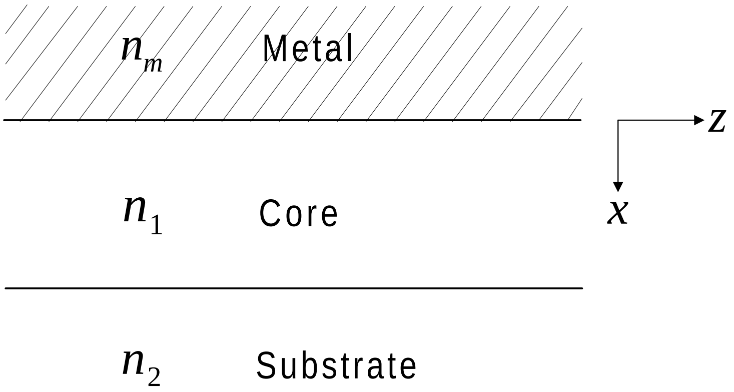

Figure 1.2: Three Layer Metal-Clad Waveguide

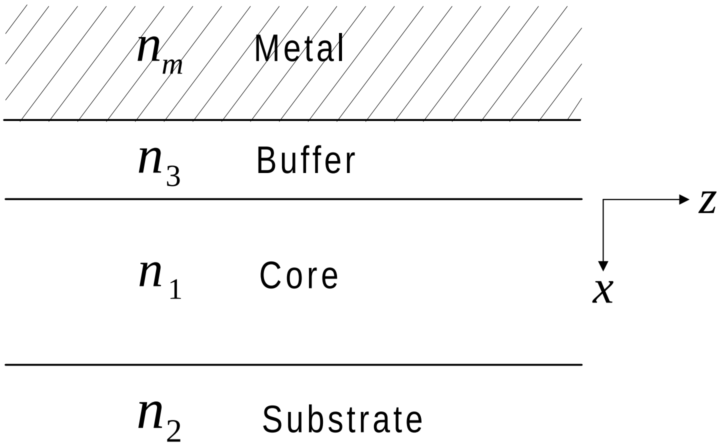

Figure 1.3: Metal-Clad Waveguide with a Buffer Layer

## 1.5 Method of Lines and other Numerical Methods

Optical waveguide problems that can be analytically solved are limited to simple structures and devices. For complicated devices, either analytical solutions do not exist in closed form or even if they exist, they are difficult to obtain. Several numerical methods have been developed to model longitudinally-varying waveguide structures. Among these methods are the Beam Propagation Method (BPM) [24, 25], Finite Difference Time Domain (FDTD) method [26], Collocation Method [27], Mode Matching Method (MMM) [28] and Method of Lines (MOL) [29, 30]. A good review of these and some other numerical methods is given in [31, 32].

The basic BPM can not be used to model waveguide discontinuities due to its inability to account for backward reflected waves at a longitudinal discontinuity. It is also an approximate method which requires the wave to be paraxial [28]. The FFT-BPM version is also known to be inefficient in problems having large index discontinuities in the transverse direction. Hence, it is good only for low contrast waveguides and for gradual bends in optical waveguides.

The FDTD method can be used to model longitudinal discontinuity problems but it requires the whole structure to be discretized and stored in computer memory. Hence to model long gratings, the FDTD requires excessively large memory. Also this is a time-domain method and the algorithm should be run for considerable amount of time to get steady state response and some post-processing may be necessary. At any rate this method is gaining popularity due to both its ease of understanding and implementation.

The Collocation Method is based on the Helmholtz equation and does not require the Fresnel approximation for its implementation [33]. In this method, the field is expanded into a set of suitable orthogonal basis functions $\phi_n(x)$ in the transverse direction. The choice of basis functions depend on the problem geometry. Since these basis are not eigen-modes of the problem, we need a larger number of basis functions to achieve accurate results.

The Mode Matching Method (MMM) or Eigenmode Propagation Method (EPM) employs eigen-mode expansion of the field, in which the discrete guided modes, the continuous radiation modes and continuous evanescent modes are taken as basis [34]. The choice of these basis functions is problem dependent. The reflected and transmitted fields are solved through a mode matching procedure.

The Method of Lines (MOL) is a semi-analytical technique used to solve partial differential equations (PDE). For an n-independent variable PDE, only (n-1) variables are discretized to obtain a system of ordinary differential equations (ODE) [35, 36] in the remaining independent variable, which can be solved analytically. This results in a higher numerical accuracy due to the reduced number of discretized variables, less computational time due to the analyticity in the remaining independent variable and smaller memory requirements as we do not need to discretize in the analytical direction. Instead of approximating the field by a series expansion of basis functions (as done in the Mode Matching Method), the second-derivative operator is approximated by a finite-difference scheme. The resulting matrix ODE is solved to find the eigenmodes of the structure. This method can account for backward reflected field due to longitudinally inhomogenous structures, which permits the analysis of planar waveguides having longitudinal discontinuities.

## 1.6 Statement of the Problem

The Method of Lines is chosen for the analysis of waveguide structures in this thesis, because it is a rigorous method and which can model high-contrast waveguides including metals. It can account for the reflected field at sudden longitudinal waveguide discontinuities, junctions and bends. The basic three-point central-difference approximation of the second derivative operator, which is used in the Method of Lines gives relatively poor estimate of the modal fields and effective indices of a multi-layer waveguide structure. Thus we will use higher-order approximations of the second derivative operator with appropriate interface conditions to improve the accuracy while using fewer discretization lines to sample the problem space. This helps to reduce the computational time required to obtain stationary solutions as well as the analysis of multiple discontinuity problems. Another improvement to MOL is achieved by using a non-uniform meshing scheme to reduce the number of required sampling points. When radiative fields are involved in the problem, we need to terminate the problem space by an appropriate absorbing boundary condition to model an infinite space. In this thesis, a Perfectly-Matched-Layer (PML)

[37] is used as an absorbing layer. In order to model a grating having many periods, the basic method is to match the tangential fields at each longitudinal discontinuity and to express unknown field values in each region in terms of the known incident field. This layer-by-layer procedure is very slow and requires a large memory in order to store the intermediate results. Our aim in this thesis is to implement a cascading and doubling algorithm which is a fast and memory efficient algorithm to model long periodic gratings taking advantage of the periodic nature of the grating [38]. MOL will be used to calculate the modal fields and effective indices of the metal-clad waveguide.

In this thesis, we will analyze two types of TM-pass metal-clad polarizers. The first polarizer is a TM-pass transmission mode polarizer and the second one is a reflection mode polarizer. We will study the insertion loss and extinction ratio of the first type of TM-pass polarizer. We will also study the effect of both the refractive index of the high-index buffer layer and its thickness.

For the second type of polarizer, we will use a grating in tandem with the first structure to achieve a reflection mode TM-pass polarizer. The spectral response of this device will be calculated for different high-index buffer thicknesses, different number of grating periods, different groove depths and different length of the polarizer. A conclusion will then be drawn about the performance of the second device. In this work, both $TE$ and $TM$ modes will be analyzed and a general purpose software will be developed.

## 1.7 Thesis Organization

This thesis is organized starting with a review of the basic slab waveguide theory and ending with the analysis of the metal-clad TM-pass polarizers. In this thesis, we present the analysis of two types of TM-pass metal-clad polarizers. The first polarizer is a TM-pass transmission mode polarizer (discussed in chapter 5) and the second one is a reflection mode polarizer (discussed in chapter 7). To our knowledge, the second type of polarizer is novel and it has not been studied previously.

Chapter one, being an introductory chapter, briefly enumerates the historical background of integrated optical systems. The waveguide gratings and metal-clad waveguides are also discussed.

The fundamental component of guided-wave opto-electronic devices is the optical waveguide which supports the optical field. That is why, the theory of the dielectric slab waveguides is presented in chapter two. The second chapter starts by introducing Maxwell's equations. By using Maxwell's equations, the wave equation is obtained and subsequently used to analyze the stationary modes of a slab waveguide. The same chapter also includes discussions of the mode number, mode cut-offs and weakly-guiding waveguide.

In chapter three, the numerical Method of Lines (MOL) is introduced. The necessary interface conditions are discussed for multi-layer structures. Besides the three-point central-difference approximation of the second derivative operator, the five-point and seven-point approximations with appropriate interface conditions are discussed. Exact results are compared to the numerical results based on the MOL in order to establish the accuracy of the MOL.

In chapter 4, the implementation and importance of absorbing boundary conditions, Mur's absorber and Perfectly Matched Layer (PML) absorber, are explained. The MOL is subsequently used to model single and multiple waveguide discontinuities.

In chapter 5, the metal-clad waveguide without a buffer layer and with a buffer layer is described and analyzed using the MOL. The effective indices and the modal fields for this waveguide structure are calculated and compared with exact results. The effect of the buffer layer refractive index and thickness is explained. The calculation of modal power and modal coefficients is presented. The performance of TE-pass and TM-pass polarizers is evaluated.

In chapter 6, the Cascading and Doubling Algorithm is described to model long gratings having thousands of periods. This algorithm is started by first finding the equivalent reflection and transmission matrices of two discontinuities joined together from their individual reflection and transmission matrices. This procedure is repeated to find the total reflection and transmission matrices of a grating. As it will be seen later, the cascading and doubling algorithm allows us to model $2^n$ periods in $n$ steps. This algorithm gives us improved speed and smaller memory requirement as compared to other methods.

In chapter 7, the TM-pass reflection mode polarizer which has periodic corrugations in addition to the metal-clad section, is modeled using the MOL and the

Cascading and Doubling Algorithm. To our knowledge, the reflection mode polarizer is novel and it has not been studies previously. The modal spectral reflectivity and transmissivity of the reflection mode polarizer are calculated for different high-index buffer thicknesses, different number of grating periods, different groove depths and different length of metal-clad section. At the end of the chapter, suggested parameters for obtaining a short polarizer length are recommended.

In the last chapter, this work presented is summarized along with conclusions and few possible future extensions are proposed.