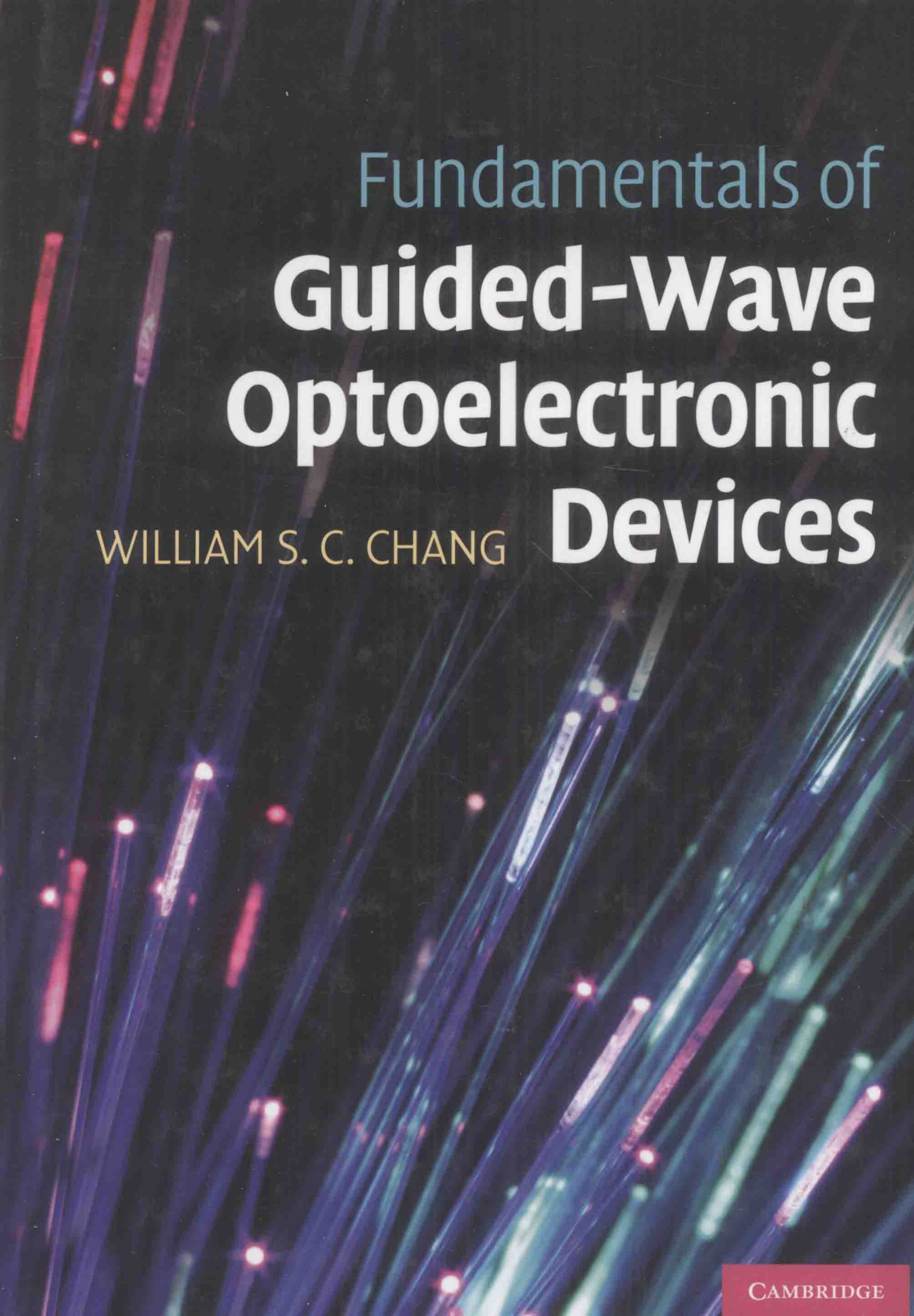

Fundamentals of Guided-Wave Optoelectronic Devices

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Fundamentals of Guided-Wave Optoelectronic Devices

Optoelectronic guided-wave devices are used in a wide range of optical fiber communication and optoelectronic systems. In such networks, the electrical and the optical characteristics of guided-wave devices, and the interplay between them, have a profound effect on system design and overall performance.

Uniquely, this book combines both the optical and electrical behavior of guided-wave optoelectronic devices so that the interwoven properties, including interconnections to external components, are easily understood. It provides the key concepts and analytical techniques that readers can apply to current and future devices. It also presents the impact of material properties on guided-wave devices, and emphasizes the importance of time-dependent interactions between electrical and optical signals. The properties of the devices are presented and compared in terms of system requirements in applications. This is an ideal reference for graduate students and researchers in electrical engineering and applied physics departments, as well as practitioners in the optoelectronics industry.

William S. C. Chang is an Emeritus Professor of the Department of Electrical and Computer Engineering, University of California, San Diego. After receiving his Ph.D. from Brown University in 1957, he pioneered maser and laser research at Stanford University, and he has been involved in guided-wave research since 1971. He has published over 200 technical papers and books, including *Principles of Lasers and Optics* (Cambridge, 2005) and *RF Photonic Technology in Optical Fiber Links* (Cambridge, 2002).

Preface

Optoelectronic guided-wave devices are used in many optical fiber communication and optoelectronic systems. In these systems optical and electrical signals are transmitted, received, multiplexed and converted by means of a variety of procedures. In guided-wave optoelectronic devices, laser radiation propagates in a waveguide and energy can be coupled effectively to and from single mode optical fibers. The properties of materials used to fabricate the waveguides have a profound effect on the phase, amplitude or directional variations of the optical waves used for the generation, modulation, switching, conversion, multiplexing, and detection of optical signals. The small lateral dimensions of the waveguide structures provide for efficient control of their optical properties by means of electrical voltages or currents. On the other hand, optical signals are converted back into electrical signals via detectors. Therefore, the electrical characteristics of these devices are as important as their optical properties. Devices may potentially be monolithically integrated optically on the same chip. This is called photonic integration. Optical components may also be integrated, monolithically, with electronic devices on the same chip. This is called optoelectronic integration. In earlier times, these were called integrated optical devices, as opposed to integrated electronic devices.

The manner in which different material properties affect the electrical characteristics as well as the propagation of optical signals in optoelectronic devices is of great importance. Also of considerable importance is the process of back and forth conversion of the electrical signals and of the optical signals. Furthermore, because the electrical signals must be received or transmitted to external circuits, how the devices are interconnected or driven by other electrical systems is also of great importance. The electrical signals may propagate at microwave frequencies within the optoelectronic devices. Therefore their performances must be analyzed and evaluated in terms of time-dependent interactions of electrical and optical waves.

A large number of books are already available in the technical literature on the optical analysis of waveguides. There are also many books that analyze the specific properties of electrical devices and circuits. This book is intended for use as a graduate level reference or text book. It provides an analysis of guided-wave devices from both the optical and the electrical points of view so that the interwoven optical and electrical properties of the devices, including their optical and electrical interconnections to external components, can be represented clearly. When appropriate, the impact of material properties on guided-wave devices is presented and the importance of time-dependent interactions between electrical and optical signals is emphasized. The book emphasizes fundamental concepts and analytical techniques rather than giving a comprehensive coverage of different devices. The intention of the author is to illustrate these concepts and analytical techniques clearly so that they can be applied to all guided-wave optoelectronic devices, including many that are not covered in this book, or have not been investigated as yet.

Optical waveguides can be divided into planar waveguides (two-dimensional) and channel (three-dimensional) waveguides. The fabrication and analysis of optical waveguides constitute the most basic knowledge needed for understanding and designing guided-wave components. Chapter 1 begins with a discussion of the formation and the modal analysis of planar and channel optical waveguides. The optical analysis presented is similar to those in other books concerned with waveguides. Differently from other guided-wave books, a two-dimensional Green's function approach is presented which could be used to analyze propagation of planar guided waves in general. Also included is a description of the materials technologies employed for fabrication of optical waveguides.

The mathematical analysis of channel waveguide modes is already complicated because of the geometry of the boundaries of waveguides. Yet, in order to understand guided-wave devices, it is necessary to analyze the mutual interactions between optical waves in two or more channel waveguides. Therefore approximation techniques such as perturbation and coupled mode analyses are introduced in Chapter 2. They could be used to analyze the coupled waveguides and the interaction of optical waves with changes in material properties. Examples of waveguide components, such as the grating filter, the directional coupler and the Mach–Zehnder interferometer, are used as examples to illustrate these approximate analytical techniques. Another powerful technique useful for analysis of multiple waveguide components is the super mode analysis. It is introduced next in Chapter 2, after the coupled mode analysis. Additional insight into the properties of guided-wave devices such as the directional coupler, the Y-branch coupler and the interference coupler can be obtained from super mode analysis.

Optical amplification and photo-carrier generation are the basis of lasers and photodetectors and they are described in many other books. In this book, how changing the material properties affects the propagation and interaction of optical waves, thereby producing modulation, switching, beam scanning, etc. in optoelectronic components is treated in detail. Electro-optical effects such as the linear electro-optic effect, the electro-absorption effect and the electro-refraction effect are discussed in Chapter 3.

In optoelectronic applications, electrical fields are created by time varying electrical voltages applied to electrode structures of the components. Analytical techniques for dealing with the time varying electrical properties of optoelectronic guided-wave structures are reviewed in Chapter 4. These techniques include the analyses of electrical fields produced by time varying voltages, the electro-optical effects produced by the electric fields, and the representation of the parameters of electro-optic devices by lumped circuit elements at lower frequencies and by traveling wave transmission lines at higher frequencies. Discussion in this chapter includes issues related to impedance matching such devices to microwave sources. Note that the frequency response and the electrical behavior of the device, in turn, place additional demands on the design of electrode and waveguide configurations.

Chapters 5 and 6 provide a description of guided-wave devices using planar and channel waveguides. The analyses of these devices utilize all the optical and electrical analytical tools, material properties and electro-optical effects described in Chapters 1 to 4. The optical and electrical performances of such devices are evaluated from the application point of view and the properties of different devices designed for the same application are compared to each other.

In planar waveguides, optical guided waves can propagate in any direction, following the contour of the waveguide layer. Summations of planar guided waves form divergent, converging, diffracted and deflected waves. Therefore, how to harness the refraction, diffraction and reflection of planar guided waves by planar waveguide devices is also the focus of Chapter 5. However, most of the applications will involve channel waveguide devices because of the ease of coupling to optical fibers, the superior electro-optical performance derived from the small lateral dimension of channel waveguides, and the advantage of small electrical capacitance of the device at high electrical frequencies. Devices that perform the same practical functions such as power division, wavelength filtering, resonance filtering, signal time delay, switching, multiplexing, and modulation are described, analyzed, and compared together. Their time-dependent characteristics are derived from combined microwave and optical analyses. Device performances are evaluated in terms of the systems requirements in applications. This is an unusual feature of the book.

Acknowledgement

The author is indebted to Professors H. H. Wieder and Paul K. L. Yu at the University of California, San Diego for reviewing the manuscript. Our mission as a university is to explain the basic principles of guided-wave optoelectronics as best we can, and to continue to improve our explanations. The author welcomes any comments from readers. Comments can be sent directly to wchang@ucsd.edu.

Contents

1 The formation and analysis of optical waveguides

1.1 Introduction to optical waveguides

Optical waveguides are made from material structures that have a core region which has a higher index of refraction than the surrounding regions. Guided electromagnetic waves propagate in and around the core. The transverse dimensions of the core are comparable to or smaller than the optical wavelength. Figure 1.1(a) illustrates a typical planar waveguide. Figure 1.1(b) illustrates a typical channel waveguide. For rigorous electromagnetic analysis of such guided-wave structures, Maxwell's vector equations should be used. Many of the theoretical methods used in the analysis of optical guided waves are very similar to those used in microwave analysis. For example, modal analysis is again a powerful mathematical tool for analyzing many devices, applications and systems.

However, there are also important differences between optical and microwave waveguides. In microwaves, we usually have closed waveguides inside metallic boundaries. Metals are considered as perfect conductors at most microwave frequencies. Microwaves propagate within the metallic enclosure. Figure 1.2 illustrates a typical microwave rectangular waveguide. In these closed structures, we have only a discrete set of waveguide modes whose electric fields terminate at the metallic boundary. Microwave radiation in the waveguide may be excited either by an electric field or by a current loop. At optical wavelengths, we avoid the use of metallic boundaries because of their strong absorption of radiation. Ideal optical waveguides, such as those illustrated in Fig. 1.1(a) and (b), are considered to have dielectric boundaries extending to infinity. They are called open waveguides. Optical guided-wave modes are waves trapped in and around the core. They can be excited only by electric fields.

1.1.1 Differences between optical and microwave waveguides

Mathematically, modes represent propagating homogeneous[1] solutions of Maxwell's electromagnetic equations in waveguide structures that have constant cross-section and infinite length. Homogeneous solutions means that these are the propagating electric and magnetic fields that satisfy the differential equations and all the boundary conditions in the absence of any radiation source.[2] There are three important differences between optical and microwave waveguide modes and their utilization.

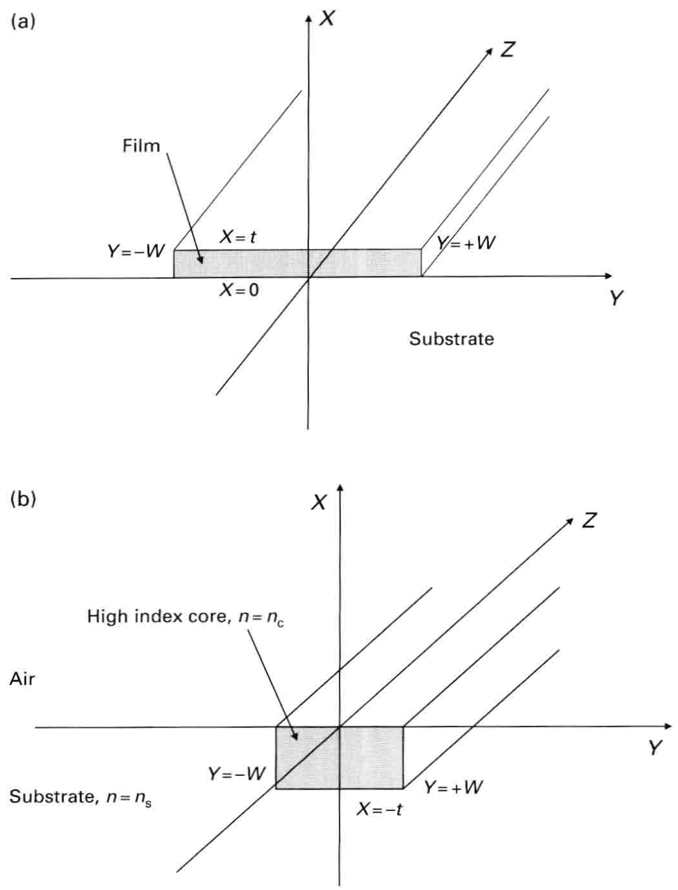

Fig. 1.1. An optical waveguide. (a) A planar waveguide. The substrate and the film are so wide in the Y direction that W can be approximated by ∞. The substrate thickness is also considered to be ∞ in the $-x$ direction. Guided-wave modes could propagate in any direction in the YZ plane. (b) A channel waveguide. The high index core ($-t \leq x \leq 0$, $-W \leq y \leq +W$) is embedded in the substrate. The core is very long in the z direction with $n_c > n_s > 1$. The guided wave propagates in the z direction.

(1) In open dielectric waveguides, the discrete optical modes have an evanescent field outside the core region (the core is often called vaguely the optical waveguide). There may be a significant amount of energy carried in the evanescent tail. The evanescent field may be used to achieve mutual interactions with the fields of other modes of such waveguides or structures. The evanescent field interaction is very important in devices such as the dielectric grating filter, the distributed feedback laser and the directional coupler.

(2) The mathematical analysis is more complex for open than for closed waveguides. In fact, there exists no analytical solution of three-dimensional open channel waveguide modes (except the modes of the round step index fiber) in the closed form. One must use either numerical analysis or approximate solutions in order to find the field distribution of optical channel waveguide modes.

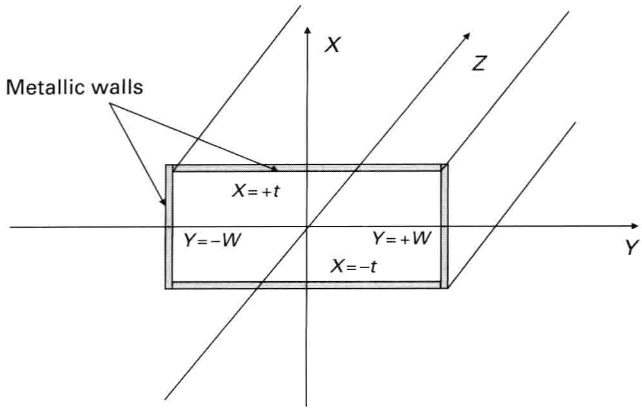

Fig. 1.2. A microwave waveguide. The rectangular waveguide has metallic walls at $y = \pm W$ and at $x = \pm t$. Guided waves propagate along the Z direction in the hollow region, $-t < x < +t$, $-W < y < +W$.

(3) In addition to the set of guided modes that have discrete eigenvalues, there is an infinite set of continuous modes in open waveguides. Only the sum of the discrete and continuous modes constitutes a complete set of orthogonal functions. It means that, rigorously, any arbitrary incident field should be expanded mathematically as a summation of this complete set of modes. At any dielectric discontinuity, the boundary conditions of the continuity of electric and magnetic fields are satisfied by the summation of both the guided-wave modes and the continuous modes on both sides of the boundary. In other words, continuous modes are excited at any discontinuity. Energy in the continuous modes is radiated away from the discontinuity. Thus, continuous modes are called radiation modes.

1.1.2 Diffraction of plane waves in waveguides

The propagation and properties of optical waves in optical waveguides can also be understood from conventional optical analysis of plane wave propagation in multilayered media. A typical optical planar waveguide is illustrated in Fig. 1.3. It has a high index film surrounded by cladding and a substrate; both have a lower index of refraction. The width of the film, the cladding and the substrate, extend to $y = \pm\infty$. The thickness of the substrate and cladding also extends to infinity in the x direction. If we analyze optical plane waves propagating in multilayered media such as that shown in Fig. 1.3, we find that there are three typical cases.

(1) In the first of these, a plane wave is incident obliquely on the film from either $x << 0$ or $x >> t$. Without any loss of generality, let us assume that the plane wave is polarized in the y direction. It propagates in the xz plane in a direction which makes an angle θ_j with respect to the x axis. The angle, θ_j, will be different in different layers, where j designates the layer with index n_j. For example, plane waves in the film with index n_1 will have a functional form, $\exp(\pm\, jn_1k \sin\theta_1\, z)\exp(\pm\, jn_1k \cos\theta_1\, x)\exp(j\omega\, t)$.

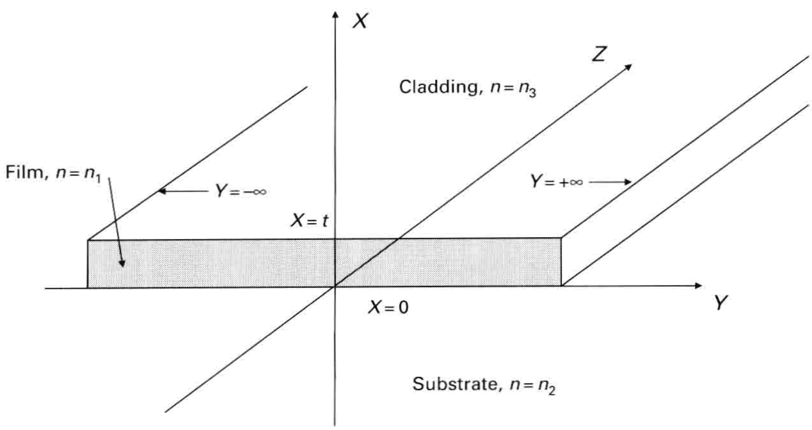

Fig. 1.3. The index profile in a planar waveguide.

There will be reflected and transmitted waves at the top and bottom boundaries of the film. The continuity of the tangential electric field demands that $n_1 k \sin\theta_1 = n_2 k \sin\theta_2 = n_3 k \sin\theta_3$ at the boundaries. There is a continuous range of real values of θ_j that will satisfy Maxwell's equations and the boundary conditions in all the layers. Plane waves with real values of θ_j represent radiation waves for $x < 0$ and for $x > t$ because they propagate in the x direction. In the language of modal analysis, the multiple reflected and refracted waves constitute the radiation modes with continuous eigenvalues β_{xj} ($\beta_{xj} = n_j k \cos\theta_j$) in the x direction, and β_{xj} is real.

(2) In the second cases, the y-polarized plane waves are trapped in the high index film by total internal reflections from the top and the bottom boundaries of the film at $x = 0$ and $x = t$. In this case the plane waves in the film will still have the functional variation of $\exp(\pm\, jn_1 k\ \sin\theta_1\, z)\exp(\pm\, jn_1 k\ \cos\theta_1\, x)\exp(j\omega t)$ with real values of θ_1. When θ_1 is sufficiently large, total internal reflection occurs at the boundaries. In total internal reflection, "$n_1 k \sin\theta_1$" is larger than $n_j k$ of the surrounding media, and θ_j (for $j \neq 1$) becomes imaginary in order to satisfy the boundary conditions at all values of z. The fields in the cladding and substrate regions, $x < 0$ and $x > t$, decay exponentially away from the boundaries. When the trapped waves in the high index film are bounced back and forth between the two boundaries, they will cancel each other because of the difference in phase and yield zero total field except at specific values of θ_1 at which the round trip phase shift of the reflections is a multiple of 2π. In other words, trapped waves can only have discrete values of real propagation constant, β_{x1} ($\beta_{x1} = n_1 k \cos\theta_1$), in the film in the x direction. It means that plane waves in the substrate and cladding (or air) only have discrete imaginary θ_j values outside the film. As we shall show later, *the non-zero (i.e. the homogeneous solutions of wave equations) waves trapped in the high index film at these specific θ_1 values constitute the various orders of guided waves. Each order of guided wave propagates in the z direction with a phase velocity equal to ω/β_1 ($\beta_1 = n_1 k \sin\theta_1$).*

(3) Let us assume that, in the third situation, the index of the substrate n_2 is higher than the index of the cladding n_3, and lower than the index of the film n_1. In this case, there are propagating plane waves in two regions of x: in the substrate and in the high index film region. The value of θ_1 is just large enough so that plane waves are totally internally reflected at the boundary between the film and the top cladding. Only the field in the cladding region now decays exponentially away from the film boundary.

When there are also index variations in the lateral direction (i.e. the y direction) similar observations, like those we discussed in (2), can be made for optical planar guided waves propagating in the lateral direction in the yz plane. Guided-wave modes in a channel waveguide such as the one shown in Fig. 1.1(b) can be analyzed as planar guided-wave modes totally internal reflected at the lateral boundary at $y = \pm W$, see Section 1.2.6. There will be evanescent fields in the y direction at $y > W$ and $y < -W$.

1.1.3 General characteristics of guided waves

In summary, optical waveguides always have a higher index core, surrounded by lower index regions, so that optical guided waves in the core can be considered as waves trapped in the core with evanescent field in the surrounding regions. There are also radiation waves (or cladding waves) that also propagate in the structure. The field distribution and the propagation constant of the guided waves are controlled by the transverse dimensions of the core and the refractive indices of the core and all the surrounding regions. In order to understand more clearly the properties of modes in the optical waveguide, electromagnetic analysis of modes in optical waveguides is presented in the next section.

The most important characteristics of guided-wave modes are the exponential decay of their evanescent tails, the distinct polarization associated with each mode, and the excitation of continuous modes at any defect or dielectric discontinuity that causes diffraction loss of the guided-wave mode. The evanescent tail ensures that there is only minor perturbation of the mode pattern for structure changes several decay lengths away from the surface of the high index layer.

Since propagation loss of the guided-wave modes is caused usually by scattering or absorption, the attenuation rate of the guided mode will be very low as long as there is very little absorption or scattering loss in or near the high index layer. The most common causes of absorption loss are the placement of a metallic electrode nearby, the absorption of the core material, and the use of semiconductor cladding or substrate (or core and cladding) that has absorption. In electro-absorption modulators or switches (discussed in Section 3.2) the absorption of the waveguide is controlled by an electrical signal so that the output optical power is modulated by the electrical signal. Besides absorption, the propagation losses are most commonly caused by volume scattering in the layers or by surface scattering at the dielectric interfaces. Volume scattering is introduced by defects in the material developed during growth or processing deposition. Surface scattering is created usually through roughness incurred in the fabrication processes such as etching and lift-off. Scattering converts the energy in the guided-wave mode into radiation modes.

The exponential decay rate of any guided-wave mode in the media surrounding the core is determined only by the indices of the layers (e.g. either the cladding index at $x > t$ or the substrate index at $x < 0$, in planar waveguides) and the β value of the mode. The $\beta c/\omega$ value is called the effective index, n_{eff}, of the mode. The velocity of light in free space c divided by the effective index is the phase velocity of the guided-wave mode in the z direction. For the same polarization, lower order modes will have a larger effective index (i.e. larger β) and faster exponential decay outside the core. For the same defects or interface roughness, modes that have a smaller effective index will be scattered more strongly into radiation modes. Therefore, higher order modes usually have larger attenuation. Any mode that has an effective index very close to the refractive index of the substrate or cladding will have large scattering loss. It is called a weakly propagating mode.

On the other hand, the evanescent tail also enables us to affect the propagation of the guided-wave mode by placing perturbations adjacent to the core of the high index layer. For example, in the next chapter, we will discuss the directional coupler formed by two waveguides placed adjacent to each other or by a grating filter fabricated on top of a waveguide.

1.2 Electromagnetic analysis of modes in optical waveguides

In order to understand clearly the electromagnetic properties of guided waves, modal analysis of an optical waveguide is presented in this section. The rigorous mathematical analysis of simple planar waveguides such as those shown in Fig. 1.1(a) will be presented first. In principle, modes of planar waveguides (or a summation of planar guided-wave modes) may propagate in any direction in the plane of the waveguide (i.e. the yz plane). However, for simplicity and without any loss of generality, the mathematical solution of the modes of the planar waveguide will be presented first just for modes propagating in the z direction. How these modes of planar waveguide (or combination of modes) propagate in any arbitrary direction in the yz plane will be discussed in terms of these z-propagating modes.

The geometry of channel waveguides is usually too complex for us to find mathematically the solutions of the Maxwell's equations in closed form. Numerical simulation programs such as *Rsoft BeamProp©* are used. The exception is the solution of the circular symmetric modes in step-index round fibers. The modes of optical fibers have been discussed in many books [1]. They will not be repeated here. We will discuss in Section 1.2.6 an approximate analysis, called the effective index analysis, of the modes of open rectangular channel waveguides such as those shown in Fig. 1.1(b). Results obtained from the effective index analysis are accurate only for well-guided modes, i.e. modes with a short evanescent tail. Nevertheless, the effective index analysis enables us to understand the basic properties of all channel guided-wave modes.

It will be clear later from the discussions of planar and channel waveguide modes that the fields of most guided-wave modes can be approximated just by the dominant component of the mode perpendicular to the direction of propagation. In other words,