ELEMENTS OF OPTOELECTRONICS & FIBER OPTICS

Chin-Lin Chen

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FOREWORD

In view of recent advances in photonic devices and optical fiber communications systems, it is clear to me that electrical engineering students should have considerable exposure to optoelectronics and fiber optics in their undergraduate educations, even if their areas of specialization are not photonics. Since photonics comprises many different disciplines, a text on optoelectronics and fiber optics, even at the introductory level, must cover a multitude of topics. It should provide a broad overview of many of those topics and an in-depth treatment of selected subjects in lightwave technology. An overview is necessary for the reader to be able to discern subtle differences in existing photonic devices and appreciate the significance of new developments in photonic technology. An in-depth discussion should help the reader prepare for future graduate studies and professional updates. With this in mind, I have organized the materials in this text into 10 self-contained chapters. They include geometrical optics and gaussian beams, the generation and detection of light, the modulation and deflection of light beams, integrated optic waveguides and optical fibers, and guided-wave components. Each subject is discussed by starting with the basic principles and with emphasis on the physical concepts. Ample sketches and illustrations are included. Often, simplifying assumptions are made and special cases are considered, so that meaningful results can be deduced without relying on advanced mathematics. Extensions or generalizations are then presented. Whenever possible, final results are couched in terms of normalized parameters. Figures of merit of several photonic devices are also introduced to facilitate comparisons.

More than enough material is presented in the text for a typical one-semester, three-credit-hour course for electrical engineering seniors. Instructors can then select a subset of topics to suit their needs. The minimum mathematics requirements are calculus and elementary differential equations. Prerequisites also include introductory courses on modern physics and electromagnetics. Some exposure to basic semiconductor physics and devices would be helpful. However, a knowledge of quantum mechanics is neither assumed nor required.

I have presented the materials contained in this text at regular classes for senior electrical and computer engineering students at Purdue University and as short courses elsewhere. I owe much to the students in those classes and short courses. They made numerous suggestions for improvement and discovered several errors and omissions in the lecture notes on which this book is based. In a sense, they are the co-authors of this book. I am indebted to my colleagues at Purdue University for their active interest and free advice throughout the years. In addition, I would like to express my sincere appreciation to Professor Gregory J. Sonek of the University of California, Irvine, Professor James J. Burke of the University of Arizona, Professor John Buck of the Georgia Institute of Technology, and Professor Monish Chatterjee of the State University of New York at Binghamton for their thorough reading and constructive critiques of the manuscript.

Finally, I am grateful to my wife, Ching-Fong, for her constant smile, everlasting patience, and continuing encouragement, and for maintaining a pleasant, comfortable, and worry-free home in which to work and to watch our children laugh, grow, and mature.

Chin-Lin Chen

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INTRODUCTION TO OPTOELECTRONICS AND FIBER OPTICS

CHAPTER 1

CHAPTER OUTLINE

1.1 INTRODUCTION

In the not-too-distant past, optics and electrical engineering were viewed as two separate disciplines, each flourishing independently of the other. However, with the invention of ruby lasers in 1960, GaAs injection lasers in 1962, and the realization of low-loss optical fibers in 1970, the two technologies quickly merged into one. Several words or terms have since been coined to identify this emerging technology. They include, for example, photonics, optoelectronics, electrooptics, etc. These terms are often used yet rarely defined. There is no generally accepted definition for any of them.

An explanation for "photonics" has been offered in a report issued by the U.S. National Research Council [1], which states:

> Photonics is concerned with the use of photons to work with or to replace electrons in certain communications, computer, or control applications traditionally carried out by electronics.

In the same report, photonics is also cited as "one of the key technologies of the information age." A more succinct definition for photonics was given by I. M. Ross in his address at the IEE's Michael Faraday Bicentennial Conference in 1991 [2], in which he stated that photonics is "the science and application of the photon." We may view the short definition of photonics as a paraphrase of the definition for electronics, "the science and application of the electron." Ross also identified two perspectives of optoelectronics:

> One is that optoelectronics is basically concerned with an integration of electronics and optics at a level where new physical phenomena are observed, and new functionality is created—functionality not possible with electrons or electromagnetic waves separated. The other perspective is that optoelectronics is concerned with optical implementation of tasks that were previously done electronically.

The use of dielectric cylinders as transmission media for electromagnetic waves is not a new concept. The propagation of electromagnetic waves along dielectric waveguides was studied by Hondros and Debye in 1910 [3]. However, low-loss (10 dB/km or less) silica glass fibers were not realized until the early 1970s. Since then, optical fibers have been used extensively in various communications systems. Lately, optical fibers have become almost synonymous with long distance telecommunications. In addition, optical fibers are used in local networks connecting offices and computers, as signal processing components, and as sensors to monitor physical, chemical, and biological variables. A new and major thrust for fiber technology is the prospect of incorporating fibers into cable television systems for bidirectional voice, video, and data transmission. This could lead to the massive deployment of fibers in cities and urban areas in the near future.

Clearly, there exist many optoelectronic devices and systems which make use of electrons and photons, and use optical fibers as the medium for transmitting electromagnetic waves. Existing devices or systems have been improved by replacing some electronic components with their optical counterparts. New devices have been conceived to take advantage of optic and electronic technologies. These new devices simply could not function with one technology alone. To design or improve such devices, an engineer must be conversant in both optoelectronic and fiber technologies. The purpose of this book is to introduce these subjects to the reader, and to provide the foundations for understanding and the tools necessary for designing these components and devices. As indicated by the title, the book covers two major topics: optoelectronics and fiber optics. Before the contents of the major topics are introduced, four specific examples that illustrate the concepts and the use of the two technologies are described.

1.2 COMPACT DISK PLAYERS

Many readers probably own, or at least have listened to, a compact disk (CD) player. The basic configuration of a CD player, so far as its reading function is concerned, is essentially the same as the playback unit of a video disk player, CD-ROM reader, or other optical data retrieval device. This is not surprising, since CD players were originally intended for use as video disk playback units for television. The early products were referred to as video long-play (VLP) systems [4].

The same basic setup also exists in equipment used for archiving optical data, laser direct patterning of semiconductor wafers, laser machining, welding, engraving, and other applications. However, the power levels involved in these systems are much higher.

Figure 1.1 is a schematic of the original VLP system playback unit. Audio and video information is encoded in the form of etched pits on the video disk. Pits of width 0.8 μm and depth 0.16 μm are etched on the flat reflecting surface of the video disk and protected by a transparent layer. The depth of the pits is approximately a quarter wavelength of the probing light in the protective transparent layer. Coherent and monochromatic light is used as the probing light, so that it can be focused to a small spot on each pit. In the original VLP design, HeNe lasers were used as the light source. Light with a wavelength of 0.633 μm from a low-power (~ 1 mW) HeNe laser is routed by prisms and focused by an objective onto the reflecting surface of the disk. Light falling on the flat reflecting surface without pits is reflected through the objective to the photodetector. Light hitting a pit is diffracted by it. Because of the divergence

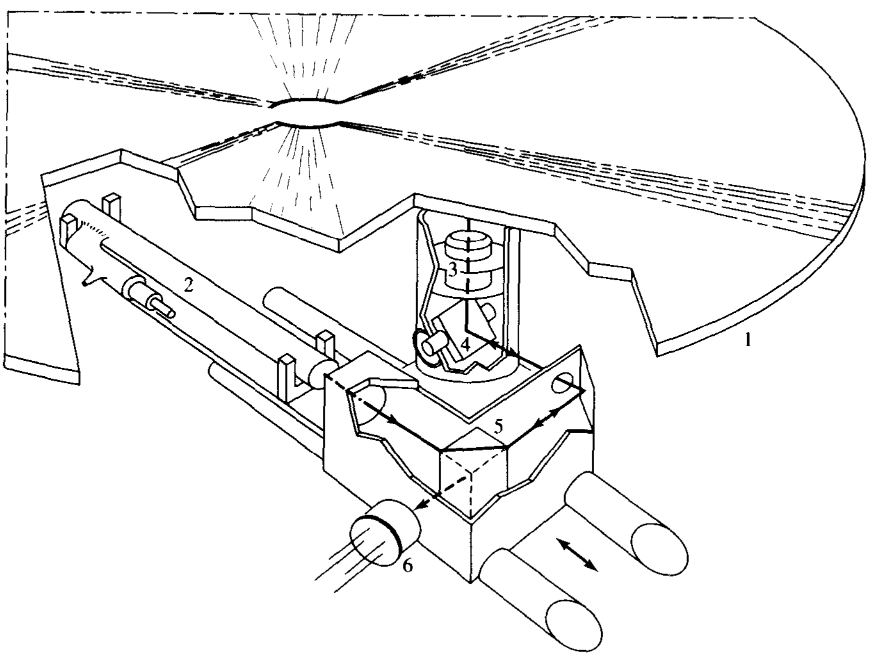


Figure 1.1 Schematic diagram of VLP playback unit (1, Optical disk; 2, HeNe laser; 3, objective; 4, pivoting mirror; 5, prism; 6, photodetector.) [4]

of diffracted light, a substantial fraction of diffracted light is diverted away from the light detector. Thus, there is a decrease in the light intensity reaching the photodetector. The phase of the light reflected by the pits is also delayed, relative to the light returning from the flat surface, by approximately a half wavelength. When two reflected beams are superimposed at the detector, the total light intensity is reduced due to destructive interference. The light intensity is converted to an electrical signal by the photodetector. The electrical signals thus generated are proportional to the light intensity incident upon the detector surface and are therefore a good replica of the information encoded on the disk.

Video disks have a diameter of 30.5 cm. Although the precise overall dimensions of the playback unit shown in Figure 1.1 are not known, a rough estimate is possible from the size of the HeNe laser. For HeNe lasers of 1970 vintage, the plasma tube is approximately 30 cm long and 5 cm in diameter. In modern CD audio players, units are smaller and HeNe lasers have been replaced by GaA1As injection lasers with emissions near 0.82 μm. Figure 1.2 is an artist's impression of the optical pickup unit of a commercially available CD player. The pickup device is about 4.5 cm in length and 1.2 cm in diameter [5]. The essential optical components are shown schematically in Figure 1.3. The discrete optical components are fabricated individually and then assembled in a robust and compact manner. Two additional features should be noted. First, the reflected light is directed to four photodetectors. Electrical outputs from the photodetectors are combined to provide the audio information, as well as the electrical signals for

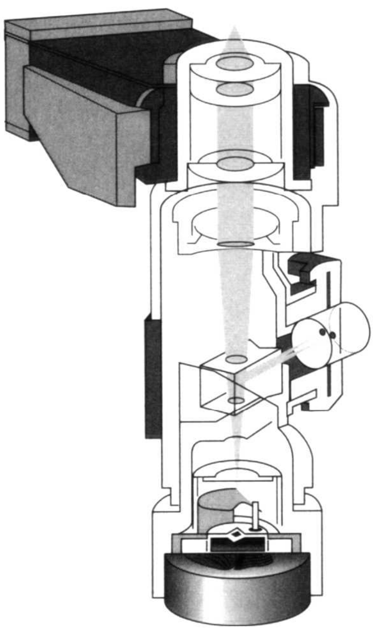
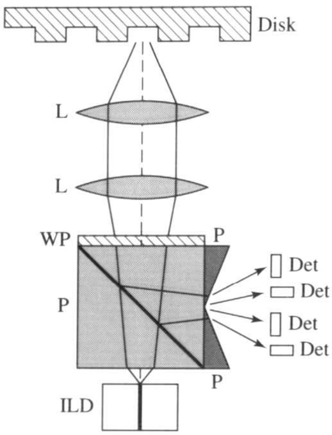


Figure 1.2 Artist's impression of the pickup unit of a CD player [5]



Det: Detector
ILD: Injection laser diode
L: Lens
P: Prism
WP: Quarterwave plate

Figure 1.3 Essential optical elements of an optical pickup unit

tracking and error correction. Second, a quarterwave plate is inserted between the beam splitter and the lenses. Because of the quarterwave plate and the polarizing beam splitter, the reflected beam is diverted to the photodetectors, rather than to the laser diode. As a result, instabilities due to optical feedback are minimized and system performance is greatly enhanced.

An integrated optic pickup unit has been reported in the literature (Figure 1.4). In this unit, optical beams are guided by thin-film waveguides, rather than propagated in an unguided manner in free space. The discrete or "bulk" optic components, like lenses and beam splitters, are replaced by their integrated optic counterparts. For example, gratings are used to both focus and split the guided beams. In addition, photodetectors are built on the same substrate used to form the thin-film waveguides, grating reflectors, and lenses [6, 7]. Note, however, that the pickup unit shown in Figure 1.4 is not yet fully "integrated," since the laser diode is attached separately to the pickup chip. In the future, it can be expected that the injection laser diode will be built monolithically onto the pickup unit. The resulting fully integrated pickup devices will be truly compact and very rugged.

1.3 INTEGRATED OPTIC TEMPERATURE SENSORS

Not all integrated optic devices are as complicated as the CD pickup unit shown in Figure 1.4. In this section, the operation of a relatively simple and yet sensitive temperature sensor is described. It is an integrated optic Michelson interfer-

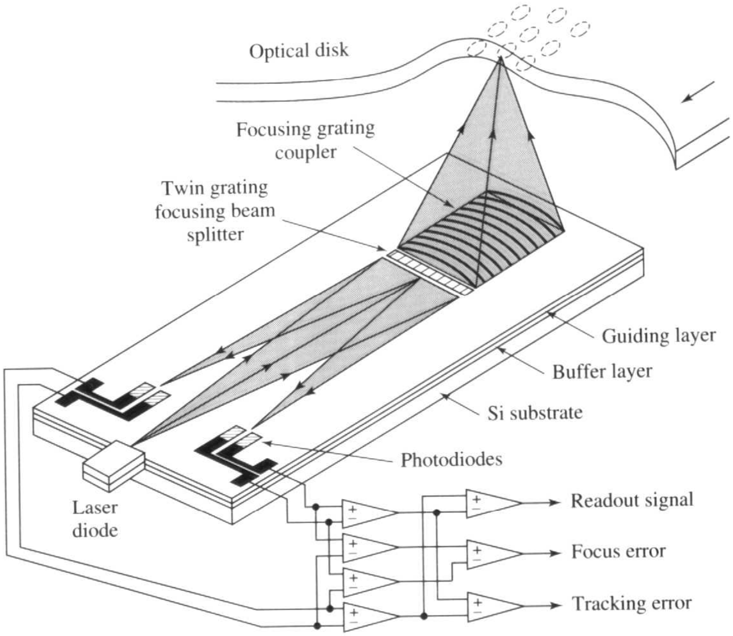


Figure 1.4 Schematic diagram of integrated optical disk pickup device with gratings for beam focusing and splitting ([7] © 1986 IEEE)

ometer. The essential components of the temperature sensor are shown schematically in Figure 1.5. In particular, the waveguide junction serves as both an optical beam splitter and a beam recombiner. The waveguides to the right of the junction have different lengths, L_1 and L_2. We will show shortly that the temperature sensitivity of the interferometric sensor increases with the path length difference, $\Delta L = L_1 - L_2$. To make the device robust, the reflectors terminating the waveguides are deposited directly on the waveguide ends.

Light of a known wavelength λ from a coherent source is fed to the input arm to the left of the junction. Because of the junction, the input is split between the two arms on the right. Let the fields emerging from the junction be E_1 and E_2. These fields traverse from the junction to the mirrors and then back to the junction. The round-trip phase delays in the two arms are $2kNL_1$ and $2kNL_2$, where N is the effective index of refraction of the thin-film waveguides and $k = 2\pi/\lambda$. Also, k can be expressed in terms of frequency f, i.e., $k = 2\pi f/c$. It will be shown in Chapter 7, "Integrated Optics," that N depends on the material properties and the waveguide geometry. We assume that the reflection coefficients introduced by the two reflectors are the same and they are set to 1 for simplicity. The fields returning to the junction are $E_1 e^{-j2kNL_1}$ and $E_2 e^{-j2kNL_2}$, respectively. The reflected fields are combined by the junction. The fields in the detector arm are:

$$E = E_1 e^{-j(2kNL_1 + \phi)} + E_2 e^{-j2kNL_2}$$

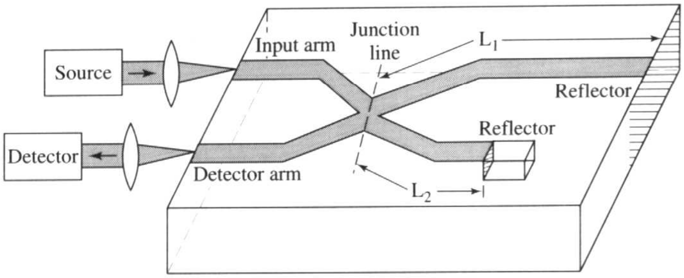


Figure 1.5 Integrated optic temperature sensor

where ϕ is the phase introduced by the waveguide junction. In Chapter 5, "Optical Detection and Detectors," it will be demonstrated that the detector output is proportional to $|E|^2$. A little manipulation will show that

$$|E|^2 = E_1^2 + E_2^2 + 2E_1E_2 \cos [2kN(L_1 - L_2) + \phi]$$

Thus, the detector output is of the form

$$V = 1 + m\cos(2kN\Delta L + \phi) \qquad (1.1)$$

where $m = 2E_1E_2/(E_1^2 + E_2^2)$. Clearly, the detector output is a periodic function of $2kN\Delta L + \phi$ and varies between $1 + m$ and $1 - m$. Both N and ΔL are temperature dependent. As temperature changes, $N, \Delta L$, and therefore V change as well. By monitoring the change in V, we infer the temperature change. This is the operating principle of the Michelson interferometric temperature sensor. To estimate the temperature sensitivity, we write $2kN_0\Delta L_0 + \phi = \Phi_0$ where $\Delta L_0 = \Delta L(T_0)$, $N_0 = N(T_0)$, and T_0 is the reference temperature. At temperature T,

$$2kN\Delta L + \phi \sim \Phi_0 + 2k\,[\frac{d}{dT}(N\Delta L)]\,(T - T_0).$$

The derivative term at $T = T_0$ is:

$$\frac{d}{dT}(N\Delta L) = \frac{dN}{dT}\Delta L_0 + N_0\frac{d\Delta L}{dT} = \Delta L_0\left(\frac{dN}{dT} + \frac{N_0}{\Delta L_0}\frac{d\Delta L}{dT}\right) \qquad (1.2)$$

The term $\frac{dN}{dT}$ is the rate of index change as temperature changes, and $\left(\frac{1}{\Delta L_0}\frac{d\Delta L}{dT}\right)$ is the linear thermal expansion coefficient of the waveguide. These terms depend on the material properties and the geometry of the waveguide cross section. Thus, $\frac{d}{dT}(N\Delta L)$ increases linearly with ΔL_0, which is also proportional to ΔL.

An integrated optic temperature sensor, as depicted in Figure 1.5, has been reported by Izutsu, et al. [8]. Their sensor was built on an $LiNbO_3$ substrate. By using published values of material properties, such as the thermal expansion coefficient of $LiNbO_3$, the specific waveguide dimensions (ΔL = 9.6 mm), and the operating condition (λ = 0.633 μm), they estimated that $\left[2k \frac{d}{dT}(N\Delta L)\right]$ is about 7. Thus, for a temperature increment of 0.44°C, $2kN\Delta L + \phi$ changes by π. In other words, a temperature change of 0.44°C would cause V given in (1.1) to change from its peak value to a valley, or vice versa. Such a variation in V can easily be monitored. The measured value is 0.32°C. As indicated in (1.2), $\frac{d}{dT}(N\Delta L)$ increases linearly with ΔL. By increasing the path length difference, the temperature increment needed to change $2kN\Delta L + \phi$ by π decreases; in other words, the temperature sensitivity increases. Izutsu, et al., predicted that this type of temperature sensor might be used to discern temperature variations as small as 0.01°C.

1.4 AN OPTICAL FREQUENCY DIVISION MULTIPLEXING DISTRIBUTION SYSTEM

The principal use of optical fibers is to transmit optical signals, with little attenuation and distortion. There are many types of fiber communications systems with various degrees of complexity and sophistication. The simplest fiber communications system consists of a transmitter at one end of a fiber and an optical detector at the other end. In such a simple configuration, the fiber transmits a single signal channel. In actuality, the fiber bandwidth is quite wide, and fibers can carry many signal channels. Therefore, a more economical use of fibers would be to transmit a large number of signal channels from several transmitters on one end to a multitude of receivers on the other end. Various signal multiplexing and demultiplexing schemes have been conceived for transmitting many signal channels over a single fiber. In this section, we will describe an optical frequency division multiplexing distribution system, originally presented by Toba, et al. [9].

In an optical frequency division multiplexing distribution system, optical signals with several carrier frequencies, separated by a small frequency separation, are transmitted in the same fiber. Each carrier is individually modulated and carries different information. For example, suppose that the optical signals have a wavelength near 1.5 μ, which in terms of frequency is about 200 THz, and that the frequency separation between neighboring channels is 10 GHz. The carrier frequencies, then, can be 200.00 THz, 200.01 THz, and 200.02 THz, etc. A block diagram of such an optical frequency division multiplexing distribution system is shown in Figure 1.6a. The optical signals are combined in a multiplexer and then fed to the fiber. If necessary, the optical signals are amplified along the way by one or more semiconductor amplifiers or, more likely, by doped fiber amplifiers. At the other end of the fiber, signals are branched out to several receivers. All receivers receive all the signal channels. The desired signal