Chapter One *Introduction*

Semiconductor laser or laser diode in similar term is the key component in optoelectronics and photonics technologies for the information and communication applications since laser was invented in 1962 [1]. Presently both technologies cover a wide area of applications as shown in Figure 1.1. The most important application of semiconductor laser is for optical-fiber telecommunication system.

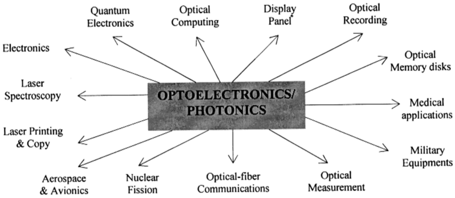

Figure 1.1: Applications of Optoelectronics and Photonics.

1.1 Development of Semiconductor Laser

The development of semiconductor laser can be briefly classified into five stages, as shown in Table 1.1. The first semiconductor laser was demonstrated in 1962 [2-5] by using GaAs laser diode. However, this early GaAs homojunction device could operate only in pulsed mode because of the high threshold lasing current. In 1963, the idea of reducing the threshold current by using heterojunction layer was proposed [6]. The heterojunction technology for the combination of GaAs and AlGaAs was developed [7, 8]. The basic concept of a direct modulation limit [9] was also discovered at this time. The second stage of the development began with the introduction of Double-Heterojunction (DH) technology. In 1970, room temperature Continuous-Wave (CW) operation of AlGaAs/GaAs DH lasers was demonstrated [10, 11]. Tranverse mode control utilizing oxide stripe, tranverse junction stripe and buried heterostructure has improved the lasing mode enabling single-mode operation of CW lasers [12-14]. In 1975, optical-fiber communication was realized with the introduction of photodetectors and optical fibers, followed by the discovery of silica optical fiber in the 1 μm wavelength region [15].

Table 1.1: The development of Semiconductor Laser.

Development stage	Time period	Laser type	Main concepts
i	1962-1969	GaAs Homojunction	Direct modulation
ii	1970-1976	GaAs Double-Heterojonction	Tranverse-mode control
iii	1977-1984	1 μm InGaAsP group	Single-mode operation
iv	1984-1990	Short wavelength	Low noise
v	1990-now	Wide spectral range	Quantum wells; red, green, blue spectrum; Surface-emitting lasers

The third stage began in 1977 with the first reported InGaAsP laser with 1.1 μm wavelength [16]. This new material for longer wavelength was developed for long haul optical-fiber communication applications. The concept of Dynamic Single-Mode (DSM) laser was proposed in 1980 [17], with the demonstration of Distributed Feedback (DFB) [18] and Distributed Bragg Reflector (DBR) [19] lasers. In the beginning of fourth stage in 1984, optical-disc devices such as CD and VCD mark a new industry application, making a mass increment in semiconductor laser chips production. Short-wavelength laser (0.6-0.98 μm) was developed in 1985 [20, 21]. The fifth stage development started in 1990 with devices emitting in wider spectral ranges and at higher performances. Surface-emitting laser [22] and quantum well (QW) laser [23] are now widely developed for further promising applications.

The worldwide semiconductor laser sales have shown high growth since its introduction in the commercial laser market in 1980. The numbers sold overwhelm all other types of lasers such as CO_2 lasers, ion lasers, solid-state lasers, dye lasers and excimer lasers, which are all classified under nondiode laser. Figure 1.2 shows that the revenues of laser diode dominate more than half of the commercial lasers market [24].

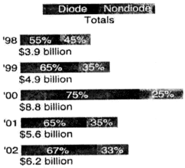

Figure 1.2: Worldwide commercial laser revenues 1998 to 2002. Ref: [24]

1.2 Basics of Optical-fiber Telecommunication System

A basic optical-fiber telecommunication system is shown in Figure 1.3. It is in this application that laser diode gives major impact. Data is sent through encoded light beams from laser diode into fibers with high capacity and at a lower cost than the copper cable transmission. The laser output is modulated to yield a digital pulse-code-modulated (PCM) signal in a series of ones and zeroes. The input signal drives the laser diode power supply (the driver), which in turn pulses the laser on and off. The light from the laser diode is coupled into the fiber. The end of the fiber is positioned by a connector to maximize the input. This part of the system is called an optical transmitter.

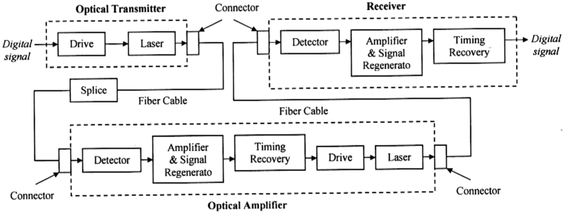

Figure 1.3: Schematic diagram of optical-fiber telecommunication system.

The fiber carries the light toward the receiver, where the light is detected and the digital signal is recovered. But the link may be long, where absorption, scattering and dispersion may degrade the signal. Optical amplifiers are needed to regenerate the signal every 50 to 100 kilometers. Thus, optical–fiber communication must include signal repeaters that consisted of detector, optical amplifier and a signal regenerator that restored the shape and intensity of the pulses. Several repeaters are needed between the original source and the final receiver. The distance between repeaters is an important factor that affects the cost and practicality of an optical-fiber communication system. At the end of the fiber network is the receiver, which consists of optical detector that detects the light and turns it back into an electrical signal, plus an amplifier and regenerator that restore the pulse shape. The output is a PCM train of digital information, the same as the input at the transmitter. Figure 1.3 also shows a splice, which is important for installation and for repairing to cut fiber cables.

1.3 1.55 μm is the most efficient operation wavelength

The loss in optical fibers is dominated by impurities in the silica-based materials that are used for fabricating fibers. Figure 1.4 shows three curves of fiber loss for different generations of fiber respectively. There are three regions or windows with local minima that is at 0.85 μm, 1.31 μm and 1.55 μm. This window refers to a wavelength region that offers low optical loss.

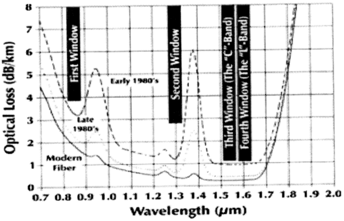

Figure 1.4: Fiber loss versus wavelength.

The 0.85 μm first window was initially used to match the LED technology and low-cost Si detectors at that time. As technology progressed, the first window became less attractive due to high 3 dB/km loss limit making the industry shifted to second window at 1.31 μm with lower attenuation near 0.5 dB/km. In 1977, the third window was developed at 1.55 μm offering lowest optical loss at 0.2 dB/km for silica-based fibers. Today, 0.85 μm, 1.31 μm and 1.55 μm are all deployed in the optical-fiber system. A fourth window near 1.62 μm is on research. Longer wavelength offer higher performance but come with higher cost. Several factors contribute to the loss spectrum in Figure 1.4 [25]. At shorter wavelengths, the loss increases due to Rayleigh scattering. At longer wavelengths, it increases due to Infra-Red (IR) photon absorption. Among other factors that may contribute to losses are bending of fiber and scattering of light at the core cladding interface. Actual total loss of fiber cables is slightly larger (by ~ 0.03 dB/km) because of splice and cabling losses.

1.4 Overview of the research

The objective of the research is to do modeling and simulation of Vertical-Cavity Surface-Emitting Lasers (VCSELs) diode at 1.55 μm. VCSELs components such as Distributed Bragg Reflector (DBR) mirror and active region will be modeled for design optimization. Based on the modeling results, a design of 1.55 μm VCSELs will be proposed. Device characteristics such as optical properties (reflectivity spectrum, optical gain, mode analysis, etc.) and electrical properties (threshold current, threshold voltage, L-I-V curve, etc.) are then simulated.

In this research, emphasis is given to Vertical-Cavity Surface-Emitting Lasers (VCSELs) diode with 1.55 μm operating wavelength. Long wavelength (1.3–1.55) μm VCSELs are promising new generation of light sources for long-distance optical-fiber communication system and is one of the key advances in optoelectronics technology. Figure 1.5 shows a schematic VCSELs device.

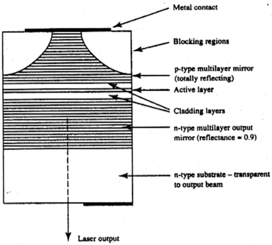

Figure 1.5: Schematic design of VCSELs device.

VCSELs have many potential advantages over the conventional edge-emitting lasers (EELs). VCSELs have a low divergence circular output beam with stable performance over temperature. It can be modulated at high data rates and have low threshold current. Plus, VCSELs offer the manufacturing advantages of wafer-scale fabrication and test, where the chips are manufactured and tested on a wafer level. It also has the ability to be produced in 2D arrays. Details of VCSELs advantages are discussed in Chapter Three.

However, a major problem of 1.55 μm VCSELs is that the active region can not be grown on GaAs-based material, which had been commercialized for 0.85 μm VCSELs. Basically, emission at wavelengths larger than the bandgap of GaAs is obtained by growing strained InGaAs QW active region, as demonstrated at 0.98 μm and 1.1 μm [26]. However, for longer wavelengths, the necessary amount of In in InGaAs would require large strains [27], making the fabrication more difficult. Thus, growth on other materials such as InP-based material is preferred. InGaAsP can be grown lattice match to InP and at appropriate compositions, it will emit in the longer wavelength range (1.3-1.55) μm. This material system has been used extensively for EELs in the same wavelength range and is available commercially. The problem with the InGaAsP system however, is that not many materials is lattice-matched for the fabrication of high reflectivity DBR mirror, which is a vital component of the VCSELs. Research into solving this issue is still being heavily pursued. Recently, various techniques have been demonstrated by using compound semiconductors and amorphous semiconductors. DBR mirror based on both compound and amorphous semiconductors will be modeled in this research in addition to the active region modeling. From the DBR mirror and active region components simulation results, a complete device design for 1.55 μm VCSELs Diode is proposed for device characterization simulation.

1.5 Dissertation Outline

The thesis begins with the Introduction in Chapter One which presents the semiconductor lasers development, the basics of optical-fiber telecommunication system, the 1.55 μm operating wavelength and the research overview. Chapter Two reviewed on the semiconductor lasers in general. VCSELs fundamentals and technology are discussed in Chapter Three. Chapter Four described the modeling and simulation software that are used in this research. The theoretical background regarding the approaches and methods for the modeling and simulation will also be explained in this chapter.

Chapter Five analyzed and discussed the modeling and simulation results of the DBR mirror, active region and the proposed 1.55 μm VCSELs device characterizations. An overall conclusions and future directions for this research are provided in Chapter Six. Finally, the appendixes which supplement the main text are given and the references cited in this thesis are listed in the end.