Chapter 1

Introduction

The main advantages of lasers over the other light sources are that their emitted light is monochromatic, coherent, directional, and that their small spot size can give very high density of energy. One of the major breakthroughs in laser technology occurred in 1962 with the invention of semiconductor lasers【1,2】. Compared with other lasers such as gas or liquid lasers, semiconductor lasers give advantages of considerably smaller size, higher efficiency, higher reliability, lower cost, and ease of use.

In addition, one of the most important advantages of semiconductor lasers is that they can be directly modulated【3】, i.e., one can readily obtain optical pulses as short as a few picoseconds by modulating the device current. It makes them appropriate for modulation over a wide range of frequencies from DC to tens of GHz. Based on these virtues, semiconductor lasers have become widely used in many types of equipment and systems so their fields of application range from optical fiber transmission systems to popular consumer electronic equipment such as data storage. Nowadays they play important roles in our daily lives.

1.1 Recent Development of VCSELs

Recently, vertical-cavity surface-emitting lasers (VCSELs) have been developed with performances comparable to those of conventional Fairy-Perot edge-emitting laser diodes (EELs)【4】. The concept of surface emission from a semiconductor laser can be traced back to 1965 when Melngailis reported a vertical cavity structure. In the late 1970's, K. Iga and his colleagues at the Tokyo Institute of Technology, Tokyo, Japan, proposed the idea of vertical-cavity surface-emitting lasers. They suggested that in order to achieve low threshold current, VCSELs should have extremely small cavity volume, high optical gain, and mirrors with extremely high reflectivity【5】. At that time, it was very difficult to obtain high optical gain in bulk materials, and it was a challenge to obtain high-reflectivity mirrors. In spite of these difficulties, they successfully demonstrated first an electrically pumped InGaAsP/InP VCSEL under pulse operation at 77 K in 1979. Several years later, they achieved room-temperature pulsed operation GaAs/AlGaAs VCSELs in 1984, and room-temperature continuous-wave operating ones in 1988【6】.

Since the mid-1980's, the state-of-the-art has progressed steadily, due to advances in epitaxial growth and fabrication technology, especially the development of distributed Bragg reflectors (DBRs) that constitute the longitudinal laser cavity, VCSELs had been taken seriously and was desirable to the commercial market. Continuous innovations in the design of mirrors, gain structures, as well as fabrication techniques for electrical and optical confinement have led VCSELs over the conventional edge-emitting laser diodes in efficiency, and surpass them by a wide margin in threshold current【7-9】.

VCSELs are desirable light source for the optoelectronic industry, because they offer low fabrication and packaging cost. The inherent advantages of VCSELs arose possibilities of various applications in optical communication, optical computing, optical storage, and so forth; therefore, several companies such as Honeywell, HP, and Vixel began to develop VCSELs toward manufacturing area since the mid-1990's. Presently, commercial products of VCSELs are extensively seen and ready to use especially in the local area networks (LANs).

1.2 Advantages and Drawbacks of VCSELs

As its name indicates, the fundamental difference of VCSEL from a conventional edge-emitting laser (EEL) is the fact that its lasing oscillation as well as the out coupling of the laser beam occur in a direction perpendicular to the epitaxial gain region and the surface of the laser chip.【10】 Figure 1.1(a) and (b) show the structures of a edge-emitting laser and a VCSEL, respectively. The VCSEL mirrors are fabricated during the epitaxial growth, thereby eliminating the cleaving process or dry etching steps used in making edge-emitting resonator facets.

On the other hand, with edge emission, the transverse and lateral modes of EEL depend on the cross section of the heterostructure gain region, which is transversely very thin for carrier confinement and laterally wide for output power【11】. The result is highly elongated near and far fields that do not match well to the circular cross section of an optical fiber. Also, the output beam is highly astigmatic. Unlike the EEL, the VCSEL circumvents the problems by having its resonator axis in the vertical (epitaxial growth) direction. With the laser emission from the wafer surface, it is possible to have a symmetrical beam cross section, with small beam divergence.

Furthermore, the overall cavity length is much shorter for a VCSEL, typically a few micrometers, as opposed to some hundreds of micrometer in the case of an edge-emitting laser. The very short cavity length makes VCSEL operation inherently single longitudinal mode. Surface emission also makes possible the fabrication of two-dimensional laser arrays. In additional to the above-mentioned benefits of VCSELs over the EEL, we summary more detail advantages of VCSELs as follows【12】:

(a) Ultra-low threshold operation is expected from its small cavity volume, resulting in low power consumption and reduced heating of the device.
(b) Wavelength and thresholds are relatively insensitive against temperature variation.
(c) Dynamic single mode operation is possible.
(d) Large relaxation frequency providing high speed modulation capability.
(e) Easy coupling to optical fiber due to low divergence circular laser beam.
(f) Long device lifetime due to completely embedded active region and passivated surfaces.

(g) High power conversion efficiency.

(h) The ability of on-wafer testing before packaging.

(i) Easy bonding and mounting.

(j) A number of laser devices can be fabricated by fully monolithic processes yielding very low cost chip production.

(k) Densely packed and precisely arranged two-dimensional laser arrays can be formed.

Moreover, VCSELs also have some drawbacks compared to edge-emitting lasers. The manufacturing tolerances on VCSEL growth are more crucial than for EELs. The perhaps major drawback of VCSELs is the strong tendency to operate with multiple transverse modes, due to the large transverse dimensions of the optical cavity. This disadvantage results in emission spectra with multiple emission wavelengths, which limits the maximum achievable fiber communicated distance due to the chromatic dispersion effects. In order to improve the performance of VCSELs, a lot of efforts have been made by scientists.

1.3 VCSELs Applications

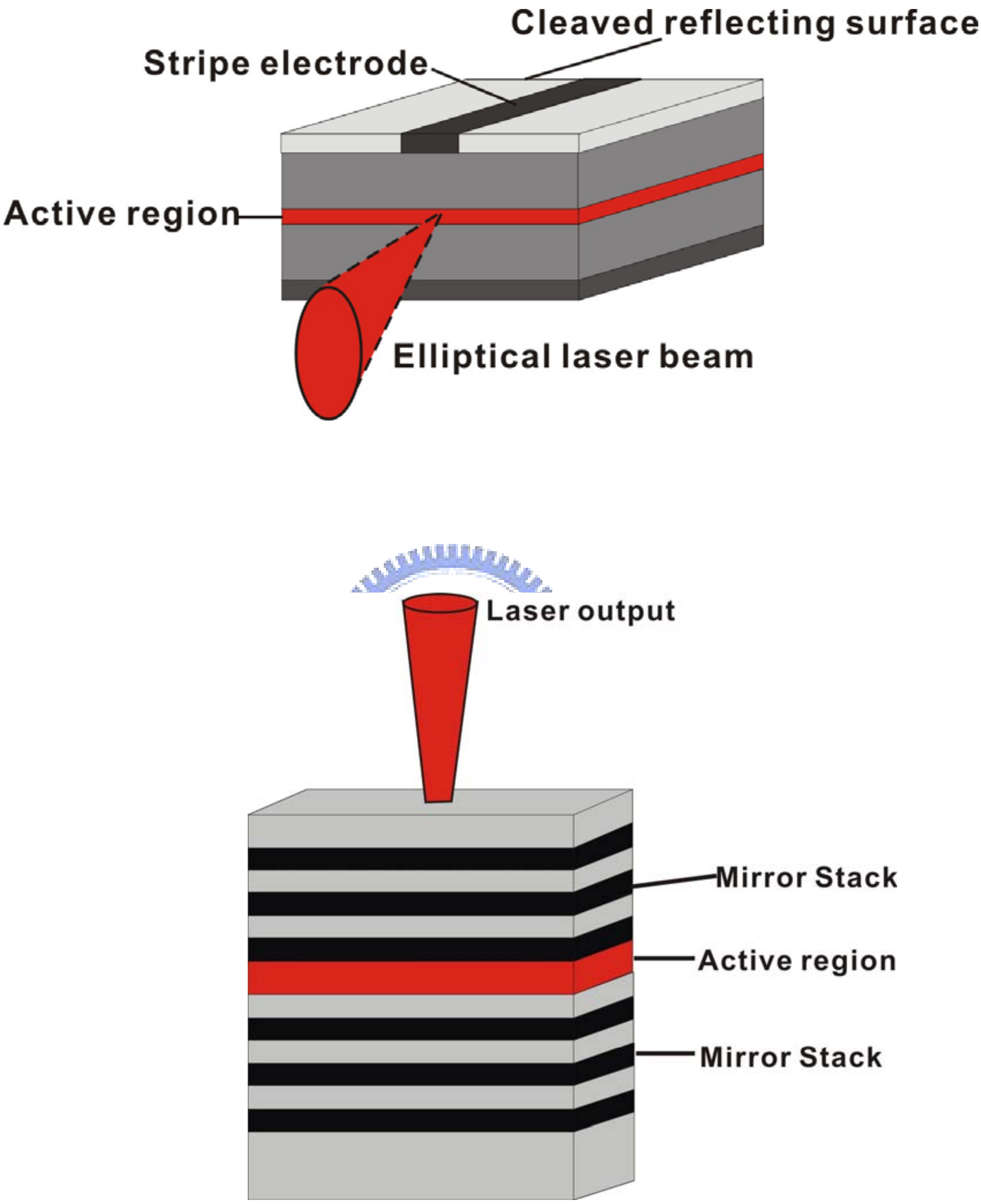
There are various commercial products in our everyday lives using VCSELs as the light emitting source such as optical fiber communications, high density optical storage, and printing, display systems, and optical sensing【13】. In addition, VCSELs can be used in parallel optical interconnect and optical information processing, which are still under extensive research and development. Near-infrared VCSELs, emitting at 850 nm, 980 nm, have demonstrated very large modulation bandwidth up to 21 GHz and 20 Gbps transmission through conventional multimode fiber. VCSEL-based modules, with speed up to 2.5 Gbps per channel for distances up to 300 meters, are now commercially available. However, due to the ever-increasing demand for bandwidth, devices operating at higher transmission rates (10 Gbps and more) will be needed in the future and have started to be demonstrated.

The possibilities of using VCSELs in optical interconnections to eliminate bottlenecks in electronic connections have been studied extensively. For example, the applications of free space optical interconnections to relieve bottlenecks associated with electrical board-to-board and chip-to-chip interconnection as well as to alleviate electromagnetic crosstalk and signal distortion【14】have been investigated. The most important applications of parallel free-space interconnections are the replacement of electrical interconnects in chip-level interconnections of high performance digital computers. Figure 1.2 shows the scheme of a parallel free-space interconnection that can be realized by integrating the microlens array with VCSEL array and photodetector array.

The development of VCSELs operating at wavelengths coupled to fiber-optic attenuation windows for telecom applications has also attracted much attention. A number of groups have reported 1.3 μm VCSELs with modulation up to 10 GHz, meeting the requirements for OC48 and 10 Gbit Ethernet applications. Recently, the first 1.55 μm VCSEL-based WDM transmission link at 10 Gbps over 50 km of standard single-mode fiber was demonstrated. Figure 1.3 shows a proposed low cost WDM optical data link via a single multimode fiber.

In the visible range, red and blue VCSELs have also emerged, and thanks to their greater speed, lower beam divergence and advantageous economics could also threaten edge-emitting lasers and LEDs in some applications such as short distance POF communications, sensors, displays, high density optical data storage and printing.

(a)



(b)

Figure 1.1 Schematic drawing of (a) an edge-emitting laser and (b) a VCSEL.

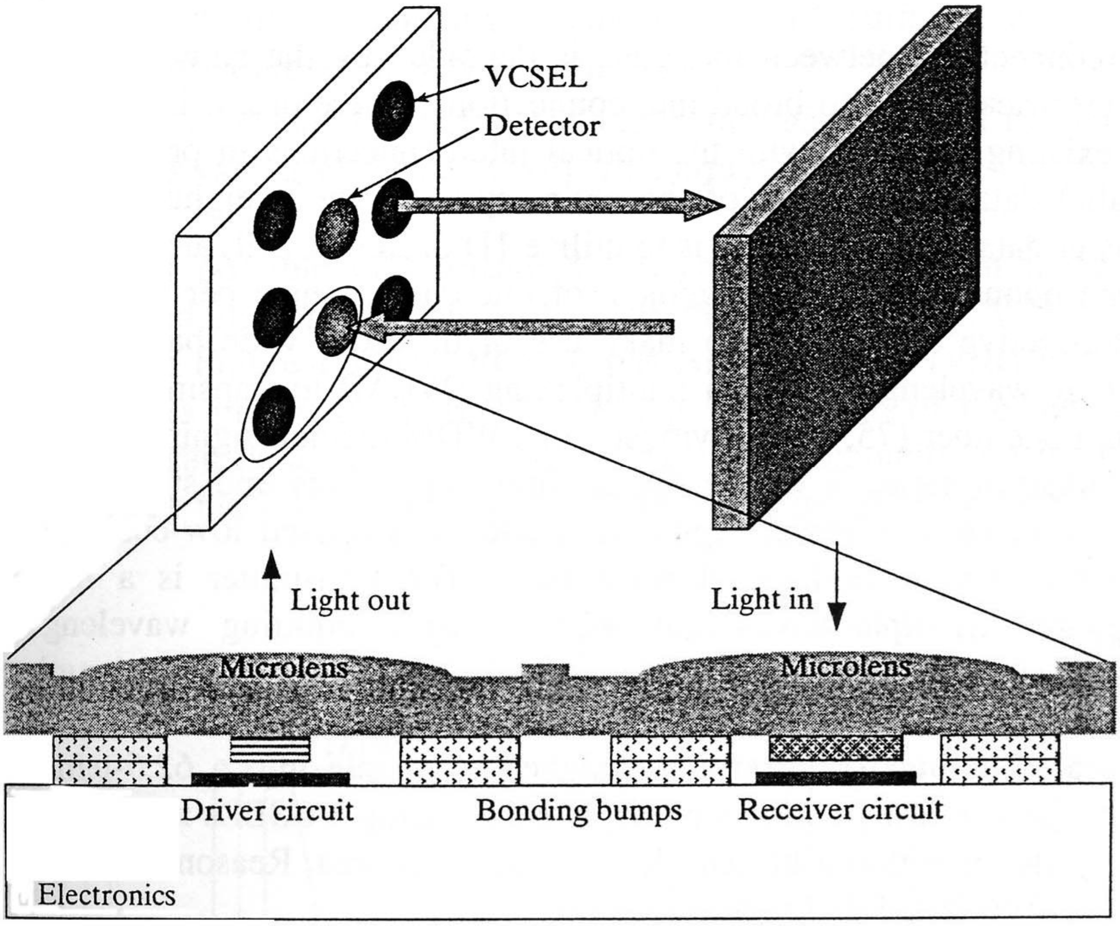
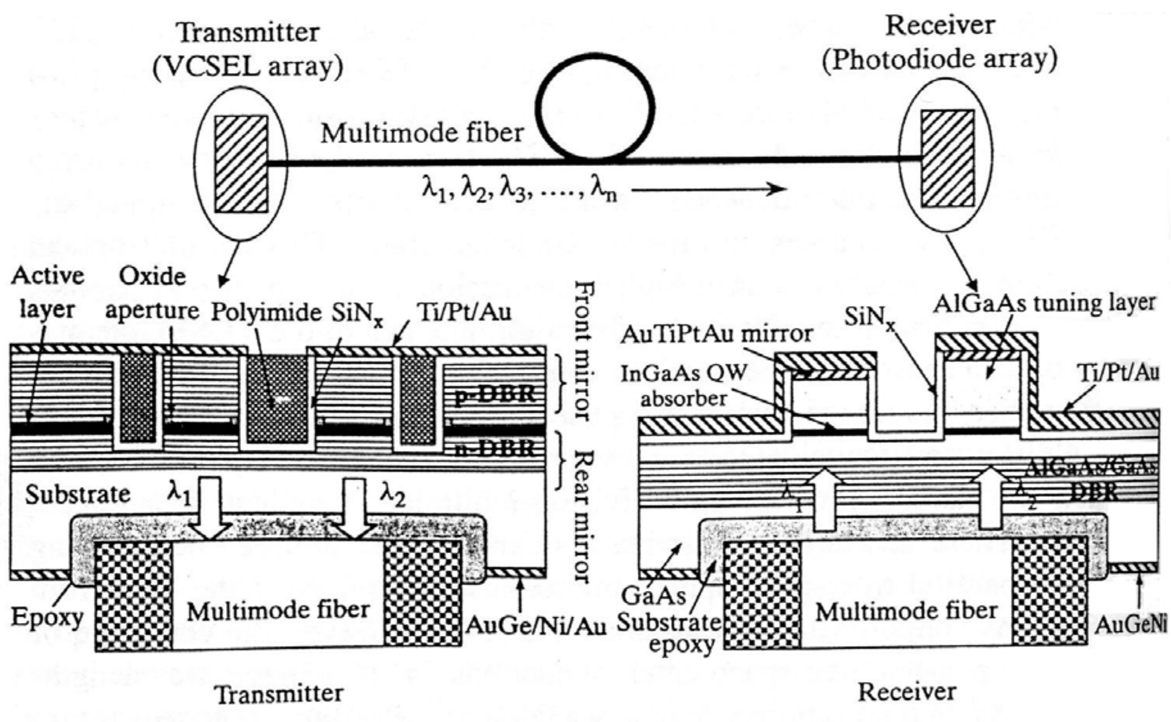


Figure 1.2 Scheme of a parallel free-space interconnection using VCSEL array and photodetector array integrated with microlens array. (Ref.【15】)

(a)



(b)

Figure 1.3 (a) A WDM optical data link transmits over a multimode optical fiber; (b) scheme of a monolithically integrated multiple [illegible] wavelengths VCSEL (transmitter) and a channel-matched wavelength-selective narrowband photodetector array (receiver). (Ref. 【16】)