A review of semiconductor lasers for optical communications

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***Abstract*—Semiconductor lasers have the potential to meet demands for next generation high speed optical networks. Their low cost, wide tunability, low power consumption, and very good spectral response make them ideal transmission sources. This paper presents a review of the current applications, commercial availability, and future directions of semiconductor lasers. Comparative analysis of these lasers identifies their deployment in different optical networks.**

Keywords: Semiconductor lasers, Fabry-Pérot (FP) laser, Distributed feedback (DFB) laser, External Cavity Diode Lasers (ECDL), Multi Quantum Well (MQW) laser, Vertical Cavity Surface Emitting Lasers (VCSEL).

I.INTRODUCTION

The semiconductor lasers were initially developed in 1962 by Robert Hall [1, 2], with the advent of this technology patents and articles started to publish; however, the technology was not mature to achieve the laser action at higher temperatures. This issue was resolved by a proposal given in 1963 by Herbert Kroemer to improve the laser action by Double Heterostructures. This made it possible to produce inexpensive commercially available semiconductor lasers, and subsequently revolutionized the optical communication.

Semiconductor lasers are popular optical communication light sources for high speed data transmission. They are accepted as "the laser of the future", due to their compactness, easy integration, and high output powers.

Coherent emission is produced in these lasers by stimulated emission, and the gain is achieved in the active medium of semiconductor by electrical injection [3]. These diode lasers are compact; therefore, they are developed on a large scale using very mature fabrication technologies. Semiconductor lasers are very efficient in converting electrical power into optical power [10].

In section II different types of semiconductor lasers are discussed in terms of their basic working, advantages, limitations, commercial availability, future directions, and applications. Section III presents a comparison of semiconductor lasers with respect to various parameters. Recent advancements in developing rapidly tunable semiconductor lasers for telecommunications are discussed in section IV. Finally, the paper is concluded in section IV.

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II. TYPES OF SEMICONDUCTOR LASERS

Following are the basic types of semiconductor lasers used in optical communication.

- Fabry–Pérot (FP) Lasers.
- Distributed Feedback (DFB) lasers.
- Multiple Quantum Well (MQW) lasers.
- External Cavity Diode Lasers (ECDL).
- Vertical Cavity Surface Emitting Lasers (VCSEL).

A. Fabry–Pérot (FP) lasers

In FP lasers, the optical feedback is achieved by the cleaved facets of the diode which causes the laser action to occur, figure 1. This makes FP lasers as edge emitting diode lasers. The emission is produced at the longitudinal modes of the cavity, and can be tuned by tuning the cavity length [4].

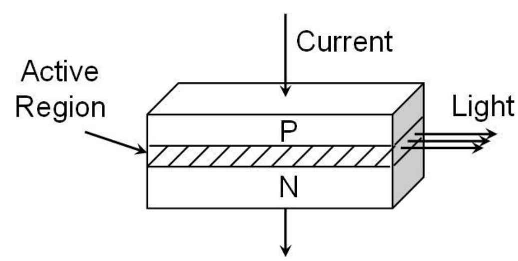

Figure.1. Fabry–Pérot laser.

FP lasers can be used for data transmission using a multimode fiber; however, high dispersion due to wide spectral line, as much as 5 nm, makes them unsuitable for long distances [6]. Additionally, Emission wavelength looses the required tolerance at 2.5 Gbps and higher data rates.

Future applications which can be exploited in this area are: Increase in bandwidth up to 15 GHz by reducing frequency roll off and parasitic effects of bias circuits using injection locking [7], external optical modulators for optical access networks [9], coarse wavelength division multiplexing (CWDM) with channels at 1.3 µm and 1.5 µm simultaneously on a single fiber [5], and multi-wavelength sources of amplified spontaneous emission (ASE) [5].

FP lasers are a very well developed technology and are readily available for many commercial applications. Multiple Application Platform FP laser, which is available commercially, has the following key features: single/multi mode output, internal modulation, and LAN extensions for instrumentation [9]. This device weighs nearly half a kilogram and is capable of operating on different optical fibers such as Flexcor™ and SMF-28 [10], with 10-40 °C operating temperatures.

B. Distributed feedback (DFB) lasers

FP lasers suffer a relatively poor spectral response due to their wide spectral line. This is improved by introducing the corrugated section in the active medium which acts as a filter, figure 2. The output emission is produced on the Bragg condition which depends upon the corrugation period. This increases the side mode suppression ratio (SMSR) and produces single longitudinal mode emission [11].

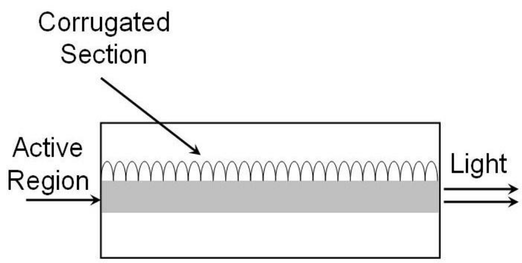

Figure.2. Distributed feedback laser

DFB lasers provide narrow spectral line as compared to the cleaved facet lasers [12], lower chirp [13], and better wavelength selectivity. These benefits make them ideal for high performance systems where single mode emission is required [6]. However, the emission wavelength near threshold is difficult to control [14].

All optical flip-flop is one of the building blocks for fast optical packet switching, as it temporarily stores the header information while the payload is routed to the correct output port. It is observed in the literature that DFB lasers can provide optical memory in an economical way, and fast switching of optical packets, with switching times as low as 45 ps, can be achieved. 40 Gbps switching by using DFB lasers as an all optical flip-flop is reported in [15].

C. Multiple Quantum well (MQW) lasers

In Quantum well lasers the active region contains thin layers (few nanometers) of potential wells bounded by high energy barriers, figure 3. The number of wells is selected upon the application, e.g., high output power requires an increased gain of the semiconductor laser, for which multiple quantum wells are used. The quantum confinement in these wells creates bound states. The number of bound states increases with an increase in the well depth, and the discontinuity increases with a decrease in the well thickness. These quantum confinements cause the light to be emitted at a higher energy, when compared to a similar double heterostructure laser [17].

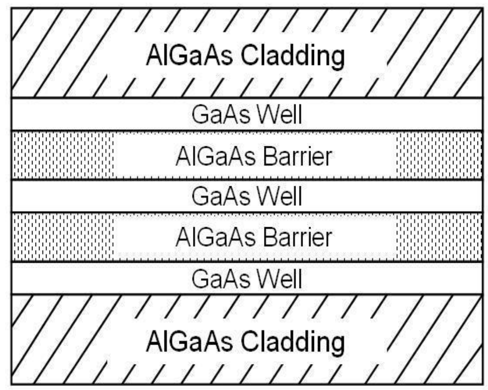

Figure.3. Epitaxial structure of a MQW laser

Quantum well lasers achieve enhanced gain as compared to conventional double heterostructure lasers [13]. Further benefits include: lower optical losses, better confinement of carriers which results in lower leakage currents, lower threshold currents, high modulation speed, and lower temperature dependence.

Strained quantum well technology can become the core technology for high performance semiconductor devices in future, due to an increased flexibility in the band engineering [18].

Commercial availability of MQW lasers is as niche as FP lasers, e.g., SANYO GaAlAs index guided laser diodes with MQW structure are commercially available as powerful sources [19], and SONY GaAlAs index guided laser diodes with MQW structure can emit high brightness optical powers up to 60 W [19].

D. External Cavity Diode Lasers (ECDL)

External cavity diode lasers are used to achieve the single longitudinal mode emission. ECDL is different from a conventional FP laser, such that one end of the diode laser has an anti-reflection coating and the resonating cavity is created using a collimator and an external mirror. Tunability is achieved using a diffraction grating, figure 4 [11, 20]. ECDL can achieve SMSR better than –40 dB which results in a narrow intrinsic line width.

However, the direction of output beam changes by rotating the diffraction grating which is not suitable for many optical communication applications.

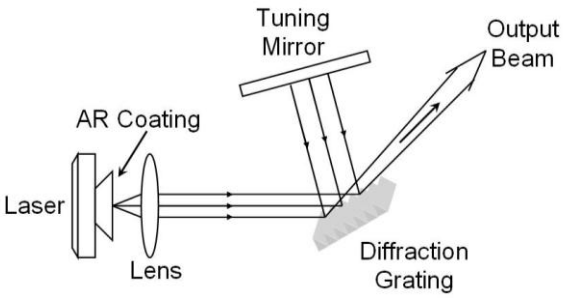

Figure.4. External cavity diode laser

External cavity diode lasers have been used to achieve many promising applications, such as: tunable continuous wave THz radiation is generated by the use of dual mode ECDL from 250 MHz to several THz [22], mode-hop free wavelength tuning over a 40 nm bandwidth (near 1550 nm) is achieved using ECDL with dielectric thin film FP filters [23], ECDL has been used in the optical system of an atomic clock [24], mode-locked ECDL has been used for data transmission in dense wavelength division multiplexing (DWDM) networks [21], and efficient non-linear optical frequency conversion.

A couple of ECDL which are available off the shelf are: TEC-100/120 furnishes output powers up to 200 mW with ~30 GHz tuning range (mode-hop free) [25], and DLX-100 can achieve output powers up to 1 W with ~15 GHz mode-hop free tuning [26].

E. Vertical Cavity Surface Emitting Lasers (VCSEL)

Vertical cavity surface emitting lasers achieve single longitudinal mode operation in a different manner. The active region is placed between two highly reflective surfaces/mirrors. These surfaces are created by alternate high and low refractive index layers to form highly reflective Bragg reflectors (99.5-99.9 %), figure 5. The laser cavity, which is created between the epitaxial layers, emits from top or bottom surface [27].

VCSELs have high wavelength stability, and they are less sensitive to temperatures up to 80 °C. They can achieve high power density up to 1200 W/cm^2. They emit circular beam as a transmitter which leads to lower optical loss. However, it is challenging to produce longer wavelengths in VCSELs. A double fusion mechanism is used to achieve this which increases the cost and complexity of the device [28].

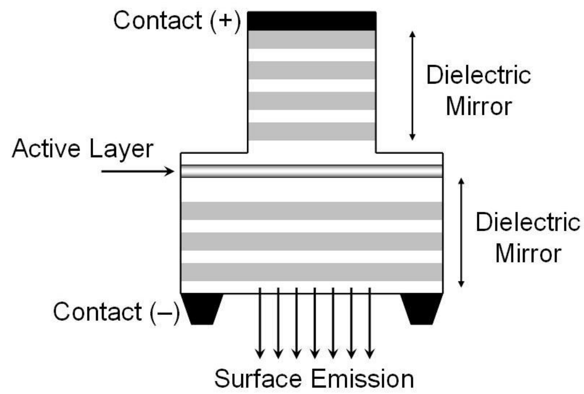

Figure.5. VCSEL epitaxial structure

VCSELs can be used as high speed transmitters due to their very fast modulation up to 25 Gbps, achieved at a low current density of 7.4 kA/cm^2 [30].

VCSEL technology is available in a wide range of products with ultra low noise, narrow line width, high output powers (up to 1 kW), and high speed modulation (>5 GHz) [27]. They are also available commercially in blue, green, and ultra-violet lasers.

III. COMPARISON OF SEMICONDUCTOR LASERS

In this section DFB, ECDL, MQW, and VCSEL are compared with respect to different parameters and their applicability is identified as a transmitter for different optical networks. Table 1 shows this comparison.

Parameters / Lasers	Tuning	Output power (in dBm)	Tuning speed	Modulation speed
DFB	Temperature	13	Slow (ms)	Fast (multi-GHz)
MQW	Quantum confined stark effect	~7	Very fast (<1 ns)	Fast (multi-GHz)
VCSEL	MEMs	Optically pumped 6, electrically pumped -3	Fast (µs)	Fast (few GHz)
ECDL	Peizo transducer	~13	Slow (ms)	Slow (<GHz)

Table.1: Comparison of semiconductor lasers.

Table 2 identifies the semiconductor laser's application in a specific network type as an optical transmitter.

Semiconductor Laser	Network type
FP laser	Short to medium range (Local & Metro) Networks
DFB Laser	Long haul network
MQW Laser	Short to medium range (Local & Metro) Networks
ECDL	Long haul network
VCSEL	Short to medium range (Local & Metro) Networks

Table.2: Semiconductor lasers used in different networks.

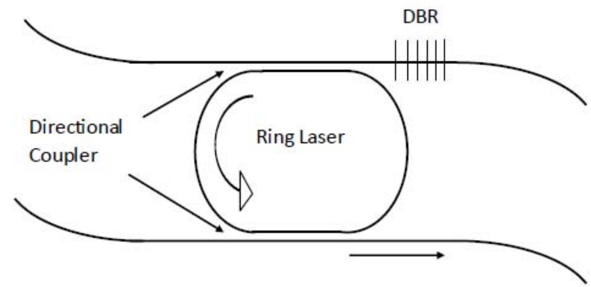

Figure.6. Tunable ring laser integrated with DBR.

IV. RECENT ADVANCEMENTS IN SEMICONDUCTOR LASERS

Optical packet switching is an attractive approach to increase the performance of a WDM network. This can be made possible by incorporating rapidly tunable sources into the present optical networks. The available solutions to achieve this are mostly based upon distributed Bragg reflector (DBR) technologies [33]. The wavelength tuning is achieved using the electro-optic effects which change the refractive index of the DBR reflectors. This results in very fast tuning of these devices; however, the added complexity of the multiple sections and slow thermal stabilization could limit the case.

Ring lasers are much appreciated for the recent advancements made in this field. They are different from the conventional edge emitting devices, such that the resonating cavity is in a ring configuration, and the optical feedback is achieved by the traveling wave phenomenon. This makes them idea for monolithically integrated devices [34]. The added benefit of ring lasers is an increased SMSR, as spatial-hole-burning is potentially avoided by the traveling wave, which results in a good spectral response of the device [35-36]. The light is coupled out of the ring cavity by a coupler, such as: directional coupler, multi-mode interference coupler, or a point coupler.

A rapidly tunable semiconductor ring laser has been demonstrated in [37], figure 6. This simple, yet faster, tuning mechanism has been achieved by integrating DBR section and a ring laser. The DBR section is used as a uni-directional seed to select the ring laser wavelength; and also, as the DBR section is external to the ring laser, the thermal effects have a lesser impact on the lasing mode. Switching time, as low as 450 ps, has been observed in this case, which is an excellent feature and could be very effective for the current fast switching applications in the optical communication.

Ring lasers are also proposed as a source for the next generation optical code division multiple access telecommunication networks [38].

V. CONCLUSION

This paper presents a review of semiconductor lasers used for optical communication systems. Their working, applications, commercial availability, and future directions have been discussed. Additionally, a comparative analysis of these lasers identifies their deployment in short to medium range or long haul networks. It has been observed that the short to medium range networks can be served with FP, MQW, and VCSEL sources. However, the long haul communication requires narrow line emission with higher stability which is provided by DFB and ECDL. Modern high speed telecommunications have pushed the drive to achieve dynamic and highly reconfigurable WDM networks, which can be realized by developing very fast monolithically integrated tunable sources. The research and development in this area will see a massive ascend in future.

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