Active Multimode Interferometer Laser Diode (Active MMI-LD) for Future High Speed Communication System

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Abstract

With the advancement in the communication systems, there is a need for large bandwidth to send more data at higher speed. Residential subscribers demand high speed network for voice and media rich services. Similarly, corporate subscribers demand broadband infrastructure so that they can extend their local area networks to the Internet backbone. Especially, the ever increasing demand for larger bandwidth that supports Triple-play services (TPS), has caused an extensive evolution in communication network topologies over the past decade. Consequently, one of the key optical access network technology under deployment is fiber-to-the-home (FTTH), which provides higher bandwidth access network service up to the home of the user. Implementation of FTTH needs laser diode capable of high speed modulation. Due to low power consumption, low cost and small size features direct modulated lasers are preferred option for low cost transmitter design. So realization of high modulation bandwidth for direct modulated laser maintaining the above mentioned feature is needed to enhance the short distance low cost data transmission.

Over the past decades, substantial efforts has been undertaken to increase the direct modulation bandwidth of semiconductor laser through various methods. Among them, injection locking, utilization of photon-photon resonance (PPR), push-pull modulation, multiline interface and short cavity scheme has been proposed and demonstrated so far. In this thesis we propose split pump configuration for active MMI-LD and demonstrated 1.55-μm InGaAsP/InGaAsP Multiple quantum well (MQW) asymmetric active Multi Mode Interferometer Laser diode (active MMI-LD). The split pumping concept has been applied for the first time in active multi-mode interferometer laser diode (active MMI LD) and significant enhancement of electrical to optical 3 dB down frequency bandwidth ($f_{3dB}$) up to
8 GHz from 2.3 GHz due to the enhancement of resonance frequency has been successfully confirmed. The device also showed single wavelength output due to asymmetric port configuration. Reported high bandwidth for split pump active MMI-LD is around 3.5 times higher than the previously reported maximum 3 dB bandwidth of active MMI-LD without split pumping section. Clear and open large signal eye diagram had also been confirmed for 2.5 Gbps, \((2^n-1)\) pseudo random bit sequence (PRBS) modulation. Moreover, the advantage of having large multimode active pumping section behind the split modulation section is the key contributor for having higher photon density in modulation section without increasing the device length. By utilizing the split pump configuration in the designed active MMI-LD, high intrinsic 3 dB modulation bandwidth of 24.6 GHz is achieved. To the best of our knowledge this is the highest reported intrinsic modulation bandwidth for active MMI-LD.

The strategy to enhance the modulation bandwidth of the asymmetric active MMI-LD has been presented and required photon density to achieve more than 40 GHz 3 dB bandwidth for direct modulation is also clarified. To open the path towards future higher speed direct modulation laser diode, the basic principle of the active MMI-LD for the incorporation of photon-photon resonance has been presented and for the first time and successfully demonstrated the occurrence of photon-photon resonance in the fabricated prototype active MMI-LD for bandwidth enhancement. The successful presence of PPR opens up the possibility of ultra-high direct modulation bandwidth 1.55 μm active MMI-LD. We also demonstrated the carrier photon resonance related intrinsic modulation bandwidth of active MMI-LD is as high as 26.4 GHz with a possibility to enhance it up to 40 GHz that eventually can team up with the PPR induced bandwidth enhancement towards the achievement of 100 GHz 3 dB bandwidth. The design criteria for 100 GHz 3dB bandwidth is also calculated from the existing experimental data and presented in this thesis. The newly proposed enhancement scheme may open up the road towards highly desired extended direct modulation bandwidth for active MMI-LD.
Chapter 1  Introduction

1.1  Overview of High Speed Communication System

1.1.1  Increasing Trend of Data Traffic in Japan

With the advancement in the communication systems, there is a need for large bandwidth to send more data at higher speed. Residential subscribers demand high speed network for voice and media-rich services. Similarly, corporate subscribers demand broadband infrastructure so that they can extend their local area networks (LAN) to the Internet backbone. Especially, the ever increasing demand for larger bandwidth that supports triple-play services (TPS), has caused an extensive evolution in communication network topologies over the past decades. Consequently, many new technologies have been deployed and standardized, with transmission media ranging from air, coaxial cables and classical twisted pair to optical fibers. Optical communication technology provides the solution for higher bandwidth, larger transmission capacity at longer transmission distance and therefore becoming a dominant access technology for the broadband access. One of the key optical access network technology under deployment is fiber-to-the-home (FTTH), which provides higher bandwidth access network service up to the home of the user. Implementation of FTTH eliminates the bandwidth bottleneck effect of the previous coper based access network. In Japan, In around 2005, when FTTH clearly took over from ADSL as the main access network, the number of FTTH subscribers has been remarkably increasing while that of ADSL subscribers has started to decline. At the end of September 2008, the number of FTTH subscriber exceeded the ADSL total and FTTH became the primary access network in Japan [1].
The nationwide FTTH household coverage ratio is more than 90% or "homes passed" is more than 70%, (In regions where the installation of CATV facilities are permitted and households in areas where installation of transit routes is complete). Above statistics indicates that high-speed broadband environments are essentially in place nationwide.

Fiber to the home (FTTH) services began in Japan with the 50 Mbit/s passive optical network (PON), which was followed by B-PON (broadband-PON). The current Gigabit Ethernet (GE)-PON system can provide services at up to 1 Gbit/s at user end.

Statistics provided by the Ministry of Internal Affairs and Communications (Fig. 1.1) shows that the speed of total broadband traffic in Japan is currently more than 2.892 Tbit/s (approximately) over fixed lines [2][3]. These figures represent an annual rate of increase of 30% for the fixed network as shown in Fig. 1.1. To satisfy and maintain the
growth of higher data rate demand, these optical networks needs to be upgraded periodically.

1.1.2 High Speed Optical Communication Network

The last mile access network solution refer to the final leg of the telecommunications networks delivering communications connectivity to end user. The last mile is typically the speed bottleneck in communication networks. Its bandwidth limits the bandwidth of data that can be delivered to the customer. For example, telephone trunk lines that carry phone calls between switching centers are made of modern optical fiber, but the last mile copper based twisted pair telephone wiring that provides access network service to customer premises has not changed much in last several decades. Copper based technologies are close to their bandwidth limit and provide only few Mb/s per user over a short distance. These technologies generate a bottleneck at the gateway of the backbone to the access networks, so to improve the last mile solution (Access network), existing copper cables are being replaced by optical fiber cables as shown schematically in Fig. 1.2. The new optical fiber based Access

![Diagram of network structures](image)

Fig. 1.2. New fiber based access networks for high speed communication
network can provide an interface between the backbone/MAN and the user premises. Latest access networks usually provide less than 1 Gbps speed for a distance less than 20 km.

At present, telecommunication network can be divided into four major sections as shown in Fig. 1.2. Among them, the new optical fiber based access network can provide a future proof high bandwidth interface between the backbone/MAN and the user premises. Latest access networks usually provide around 1 Gbps speed for a distance of less than 20 km. Fiber installations are happening at an exponential growth rate in Japan, with real data showing the trend in Fig. 1.1. The network topology of interest for most FTTX deployment is the passive optical network (PON). Next sections will provide a brief overview of the evolution of PON technologies and the optical transmitter required for their deployment.

1.1.3 Meeting Future Capacity Needs / Technology Trends

Although PON technology is mature for backbone networks, its speed, user handling capacity and longer transmission distance is still considered for access networks. Next generation optical access networks will need to provide broadband services to many concurrent users. This presents great challenges in terms of meeting the ever increasing demand of large capacity, low latency, and high security in real time applications. The level of service provided to the customer can be compromised if the network as a whole has insufficient capacity or if a bottleneck is created in any part of the network. So the existing networks need to be upgraded to meet forecast capacity needs. During last two decades, research and development has increasingly focused on the passive optical network (PON) networks. Standardization bodies such as the International Telecommunications Union (ITU) created the APON standard In the late
1990s, later a newer version was created called the broadband PON, or BPON standardized in March of 2001. Designated as ITU-T G.983, this standard provided for 622 Mbits/s downstream and 155 Mbits/s upstream. ITU-T G.984 Series GPON (Gigabit PON) is an evolution of the BPON standard. It delivers 2.488 Gbits/s downstream and 1.244 Gbits/s upstream. The latest under deployment version of GPON is a 10-Gigabit version called XGPON or 10G-PON (ITU-G.987). XGPON’s maximum rate is 10 Gbits/s (9.95328) downstream and 2.5 Gbits/s (2.48832) upstream. The Institute of Electrical and Electronic Engineers (IEEE) developed separate PON standards based on the EPON 802.3ah. The raw line data rate of IEEE GEPON is 1.25 Gbits/s in both the downstream and upstream directions. There is also a 10 Gbit/s Ethernet version available. The actual line rate of that 10G-EPON is 10.3125 Gbits/s. The primary mode is 10 Gbits/s upstream as well as downstream. A variation of that standard uses 10 Gbits/s downstream and 1 Gbit/s upstream.

At present, time division multiplexing (TDM)-based PON standards, such as gigabit Ethernet PON (GE-PON) and gigabit-capable PON (G-PON) are dominant in different countries in the world. A laser on a wavelength (λ) of 1490 nm transmits downstream data. Similarly upstream data transmits on a wavelength of 1310 nm. If TV is being distributed, a wavelength of 1550 nm is used. However, because the whole range of bandwidth is shared by all users in the system, so each user gets access to limited data rate, often reduced to megabits per second [4]. The IEEE and ITU(G989) are currently defining WDM standards and proposed NG-PON2 as the long-term next generation access network to provide 40 Gb/s speed. Recently, studies have been carried out on NG-PON2 enabling technologies, such as wavelength division multiplexed PON (WDM-PON), orthogonal frequency division multiplexing PON (OFDM-PON) and
time and wavelength division multiplexed PON (TWDM-PON). Amongst these technologies, TWDM-PON has been selected as the path toward the second stage of the next-generation PON (NG-PON2) because it supports backward compatibility, flexibility and static sharing [4]. High-end business users and mobile front-haul/back-haul for next generation wireless systems that highly rely on symmetrical data rate services are believed to be the main deployment drivers for NG-PON2 [5].

As shown in Tab. 1.1, the bandwidth of the network is increasing rapidly to meet the demand. New standard may become completely available for commercial
deployment by the end of 2015. Now researchers are also focusing on technology that can enable higher bandwidth for the FTTH user. Promising candidates are Ultra-OFDM, Ultra Dense-WDM and OFDM/WDM PON. So technology trend suggests that the access network’s transmitter unit for the next generation network must be upgraded with a suitable higher speed option. In present access networks, directly modulated lasers (DMLs) are the optical transmitter of choice. Also for future PON based access network, directly modulated lasers are the lowest-cost choices for the optical network units (ONU) in time and wavelength division multiplexed passive optical network (TWDM-PON) systems [6]. Next sections will provide a brief overview of the directly modulated laser currently deployed in optical network.

1.1.4 Transmitter for High Speed Optical Network

Due to constantly increasing demand of communication bandwidth, future optical access technologies will dominate the last mile network and the most important part of the link is the laser diode, which ultimately dictates the available bandwidth of the transmitter. Unlike long haul and metro networks where higher cost can be tolerated and absorbed by the service and volume, access applications require low hardware cost and low operation expense to make the transmission technology viable. Consequently, directly modulated lasers (DML) can be used in cost sensitive optical links due to lower cost, compact size, low power consumption, and high output power characteristics[7], when compared with other transmitter sources using external modulators (EM), such as electro-absorption modulators (EAM) or Mach-Zehnder modulators (MZM) [8],[9]. Semiconductor lasers has high electrical/optical conversion efficiencies and can be directly modulated up to GHz frequencies by modulating the drive current. Furthermore, the emitting area of laser facet is compatible with optical fiber core sizes, leading to high
Another important consideration for access networks is the modulation technique employed at the ONU's. As compared to external modulation (EM) schemes such as electro absorption modulator (EAM) or Mach-Zehnder modulator (MZM), direct modulation lasers provide a cost effective techniques to modulate light waves in cost sensitive metro and access optical links. So the use of a directly modulated laser as optical transmitter has the advantage of simple optical system design by elimination of relatively complex solutions such as external modulation utilizing continuous wave lasers followed by electro optic modulators or integrated electro-absorption modulators and associated optics. Due to the above mentioned advantages, directly modulated lasers are already widely deployed in use in present optical network as shown in Tab. 1.2. Their application is mostly limited to short and medium reach network with limited modulation speed up to 10 Gbps.

Tab. 1.2. Directly modulated laser in present optical network

<table>
<thead>
<tr>
<th>DWDM/CWDM</th>
<th>GE-PON G-PON</th>
<th>10GPON XGPON</th>
<th>DWDM Cable Television (CATV)</th>
<th>GbE 10 GbE SAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5µm (2.5Gbps&lt;100km) (10Gbps&lt;100km)</td>
<td>DS 1.49 µm &amp; 1.55 µm US 1.3 µm</td>
<td>US 1.27 µm</td>
<td>DS 1.5µm</td>
<td>0.85 µm (&lt;500m) 1.3 µm (&lt;10km)</td>
</tr>
</tbody>
</table>

However, as the bit rates of these systems will increase from 2.5 Gbit/s to 10 Gbit/s and gradually towards 40 Gbit/s, so their performance needed to be improved to meet future transmitter requirements. More advanced directly modulated laser structures with lower chirp are likely to be the preferred option for 1550 nm, where dispersion in standard single mode fiber is higher. So researchers around the world concentrated on finding a solution for higher bandwidth direct modulation laser. Some of the existing method for increasing direct modulation bandwidth is presented in brief in next sections.
1.2 Current State of The Art: High Speed Laser Diodes

1.2.1 Different Direct Modulation Bandwidth Enhancement Schemes

Optical Injection Locking:

Low noise performance in combination with single frequency operation is significantly difficult to achieve in high power lasers, because of difficulty in utilizing very low noise pump sources and significant thermal influences. Moreover use of optical filter inside the laser resonator can degrade the power efficiency and tend to fail at high output power level and not desirable for high power laser diodes. Injection locking technique is better suited in this scenario and applied mainly to continuous wave single wavelength laser sources for direct modulation bandwidth improvement. Injection locking is a process where high output power is generated from a slave laser and its noise level is reduced by injecting output of low intensity noise, low phase noise and low power typically more stable master laser as illustrated in Fig. 1.3. Injection locking occurs by coupling the light from the master laser into the slave laser cavity via a suitable
coupling method. The locking occurs when a laser oscillator is disturbed by a second optical oscillator operating at nearby frequency causing it to have essentially identical frequency as the second oscillator due to strong coupling and satisfaction of necessary locking range oscillation frequency condition. Generally high power injection is needed for more tolerance of frequency difference and the power of the injected signal typically is much lower than the slave laser free running output power. Potential advantages includes resonance frequency enhancement, modulation efficiency improvement, reduction of nonlinearity[10], Reduction of relative intensity noise[11], reduction of chirp[12] and reduction of linewidth enhancement factor[13]. Problem associated with this method includes requirement of large injection power, heating, gain compression, low frequency distortion[10] and stability of locking[14],[15]. It has been demonstrated that, under stable injection locking, the modulation bandwidth can be increased significantly[16]. Recent demonstrations include enhancement of the resonance frequency beyond 100 GHz in a directly modulated strongly injection locked laser[17].

External Modulation:

External modulated lasers are more stable solution for long distance communication and frequently used in WDM systems. Most commercial system contains integrated package of CW laser diode and the external modulator as a single unit. In external modulator the laser power is generally modulated in an external cavity. Continuous wave (CW) emission produced by DC biasing a laser diode is feed into an external modulator which modulated the CW signal into the preferred optical data streams. For most transmitters, the modulation process not only changes the light’s amplitude but unfortunately the modulation process also changes its phase or frequency. This unwanted frequency modulation (FM) is called chirp and causes the spectral
linewidth to broaden. External modulation can avoid nonlinearity and excessive chirp better than direct modulated laser [18]. Also the narrow linewidth can be obtained with external modulation that not only reduces the dispersion penalty, but also permits a closer channel spacing in a dense wavelength division multiplexing (DWDM) system. External modulator can provide better extinction ratio (ER). Moreover, maximum ER of externally modulated EA modulator can easily exceed 41.5 dB [19]. Mainly there are two types of external modulators are common for external modulation scheme. A brief overview of them is presented in the following section.

Electro-Absorption Modulators: With the application of applied voltage the effective bandgap $E_g$ of a semiconductor material decreases. Electro-absorption modulator’s working principle is based on the fact. Electro-absorption material will behave transparent without external voltage. If the energy ($E = h\nu$) of the chosen frequency of incoming light wave is smaller than the bandgap. On the other hand, when an external voltage is applied, the effective bandgap will be reduced, and the incoming light wave will be absorbed by the material ($E > E_g$). In this manner, it is possible to achieve optical modulation by properly selecting the signal wavelength so that it experiences a significant change in absorption when the modulation voltage containing electrical data is applied. Two type of mechanism can be utilized in EA modulator namely Franz-Keldysh effect in bulk and Quantum confined stark effect (QCSE) in quantum well structure. Advantages of EA modulator includes low driving voltage, low/negative chirp, high speed, lesser polarization dependence, Integration with DFB laser. It also allows a single optical power source to be used for large number of information carrying beams. High band width (90 GHz) is reported using this type external modulation scheme[20].
Electro-Optic Modulators: Electro-optic modulator and based on the change of the refractive index of crystals under an external electric field. A change in refractive index itself does not modulate the light. However, using an interferometric structure, such as the Mach-Zehnder structure enables the conversion of induced phase modulation into the desired intensity modulation. An example of MZI based electro-optic (EO) external modulator is shown in Fig. 1.4. If a time dependent voltage \( V(t) \) is applied to one of the waveguide of the modulator, its refractive index will become time dependent on the input voltage, consequently the signal transmission of the Mach-Zehnder interferometer will also depend on time. If a continuous optical wave (CW) is applied to the input of the modulator, the output power will thus be modulated according to the electrical data \( V(t) \) applied in the arm of MZI. Mach-Zehnder modulators are usually employed by placing complimentary signals or opposite phase shift in its arms to minimize chirp and this technique is known as push-pull modulation. High band width (>70 GHz) is reported using this type external modulation scheme [21]. High serial

Fig. 1.4. External Mach-Zehnder modulator
transmission rate of 100Gb/s is also reported for this type of external modulation scheme[22], [23].

External modulators are currently predominant, high performance and necessary solution for high frequency modulation but are very costly and are large in size. So they are employed for high performance, high cost, and long distance communication systems. At the same time researchers are working hard to improve the direct modulation bandwidth to reduce the transmitter cost for long distance communication.

**Monolithic Integration for Multiline Systems:**

Since it was difficult to achieve 100 Gbit/s by cost effective on off keying (OOK) format. Consequently for future data communication beyond 100G, such as 400G and 1T, the use of a multilane system as in the 100GbE to fulfill the system’s transmission capacity requirement is almost unavoidable. At the same time, increasing the data rate of serial lanes is also a very important for reducing the number of lanes. Since the volume of the transceiver is usually limited, a large number of lanes make it impossible to place the related devices in a limited area. Therefore, for beyond 100G optical communications, researchers are taking up the challenge to make a compact multiline transmitter, in which the data rate of each lane is over 25G to 100G. This method of increasing the data transmission speed of integrated transmitter uses multiple transmitter with optical multiplexer integrated in the same platform for a single compact high speed transmitter. However the requirement of the increased serial data rate is still important for reducing the required number of wavelength lanes, which will lead to smaller transmitters, lower power consumption, and reduced fabrication cost. 160-Gbit/s
transmitter optical subassembly based on 40 Gbit/s × 4 monolithically integrated light source is reported by NTT for future network application [24].

Short Cavity Scheme:

Shortening the laser cavity is one of the effective way to reducing the photon lifetime and consequently the increment of the modulation bandwidth. Theoretical description of the short cavity effect is explained in chapter two for better understanding of the short cavity scheme. Utilizing short cavity combined with high gain, high mirror reflectivity and strain quantum well, direct modulation speed ranging from 40 to 56 Gbps has been reported recently[16]-[18]. Some of the complexity involved in shortening the length of the active region are increment of chip resistance, heating, increment of threshold gain, necessity of waveguide integration to facilitate cleaving, requirement of facet coating, increased device complexity and reduced single mode yield.

Photon-photon Resonance:

In addition to this carrier photon resonance (CPR), there are also higher order resonances like the photon-photon resonance (PPR), which is caused by the revolution of a photon within the multimode section of active multimode interferometer laser diode[28]. More in depth discussion about the PPR scheme of bandwidth increment is discussed in chapter two and chapter six. Using this higher order resonance effect 40 Gbps directly modulated laser has been demonstrated by multiple researchers [29],[30]. Careful design consideration is needed for getting the flat response between the resonance peaks.
1.2.2 The Development of High Speed Communication LDs

Coherent light emission from a gallium arsenide (GaAs) semiconductor diode (the first laser diode) was demonstrated in 1962 by two US groups led by Robert N. Hall at the General Electric research center [31] and by Marshall Nathan at the IBM T.J. Watson Research Center [32]. Since 1962 semiconductor laser diode have been developed rapidly and became the most important component for the high speed optical communication. The researchers are focused on how to improve the modulation bandwidth, temperature tolerance, modulation speed and increase transmission distance at low cost. To improve those characteristics, extensive research work has been carried out. Classically fiber based systems have been used for data communication and telecommunication applications employing lasers at 1.3µm and 1.55µm due to natural properties of silica fiber. Consequently researchers are working reluctantly to increase the bandwidth of laser capable of lasing in those wavelengths.

The benchmark transmitters in terms of speed and data operation are summarized in Tab. 1.3 to Tab. 1.5. From the tables, we can see a lot of research work has been conducted to improve the 3dB bandwidth of the laser for high speed large signal modulation performance of the device. But the complexity of device structure is also increasing with the increasing bandwidth moreover the extensive research is necessary to increase the 3 dB bandwidth of laser diode beyond the conventional limit imposed by different physical parameter.

Tab. 1.3. Recent reports of 25 Gbps direct modulation

<table>
<thead>
<tr>
<th>Name of research organization</th>
<th>Material system</th>
<th>Cavity</th>
<th>$\lambda$ [µm]</th>
<th>BW</th>
<th>Active region length</th>
<th>Temp [ºC]</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fujitsu/OITDA</td>
<td>AlGaInAs</td>
<td>DFB</td>
<td>1.3</td>
<td>?</td>
<td>150 µm</td>
<td>70</td>
<td>Electron.[33] Lett. 2008</td>
</tr>
<tr>
<td>Name of research organization</td>
<td>Material system</td>
<td>Cavity</td>
<td>λ [µm]</td>
<td>BW [GHz]</td>
<td>Active region length</td>
<td>Temp [ºC]</td>
<td>Publication</td>
</tr>
<tr>
<td>------------------------------</td>
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</tr>
<tr>
<td>NTT</td>
<td>AlGaInAs</td>
<td>DFB</td>
<td>1.3</td>
<td>BW&gt;12GHz at 25ºC</td>
<td>200 µm</td>
<td>85</td>
<td>OFC[34] 2009</td>
</tr>
<tr>
<td>Finisar</td>
<td>AlGaInAs</td>
<td>DFB</td>
<td>1.3</td>
<td>BW&gt;19GHz at 27ºC</td>
<td>200 µm</td>
<td>45</td>
<td>OFC[35] 2009</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>AlGaInAs</td>
<td>DFB</td>
<td>1.3</td>
<td>BW&gt;20GHz at 25ºC</td>
<td>250 µm</td>
<td>25</td>
<td>IPRM[36] 2009</td>
</tr>
<tr>
<td>Hitachi/OITDA</td>
<td>AlGaInAs</td>
<td>DFB</td>
<td>1.3</td>
<td></td>
<td>160 µm</td>
<td>95</td>
<td>ECOC[37] 2009</td>
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<tr>
<td>Hitachi/PETRA</td>
<td>AlGaInAs</td>
<td>DFB</td>
<td>1.3</td>
<td>BW&gt;16GHz at 85ºC</td>
<td>150 µm</td>
<td>100</td>
<td>CLEO[38] 2010</td>
</tr>
<tr>
<td>Fujitsu / Petra / Univ. of Tokyo / QD Laser</td>
<td>Quantum dot</td>
<td>FP</td>
<td>1.3</td>
<td>11 GHz at 25ºC</td>
<td>400 µm</td>
<td>RT</td>
<td>CLEO[39] 2010</td>
</tr>
<tr>
<td>Fujitsu/PETRA</td>
<td>AlGaInAs</td>
<td>DFB</td>
<td>1.3</td>
<td>BW&gt;20GHz at 50ºC</td>
<td>125 µm</td>
<td>50</td>
<td>OECC[40] 2010</td>
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<tr>
<td>Mitsubishi</td>
<td>AlGaInAs</td>
<td>DFB (+WG)</td>
<td>1.3</td>
<td>250 µm</td>
<td>150 µm</td>
<td>50</td>
<td>ISLC[41] 2010</td>
</tr>
</tbody>
</table>

Note: Modulation speeds are 25 to 26 Gbps

Tab. 1.4. Recent reports of 40 Gbps direct modulation
<table>
<thead>
<tr>
<th>Name of research organization</th>
<th>Material system</th>
<th>Gbps</th>
<th>Temp [ºC]</th>
<th>BW [GHz]</th>
<th>Cavity</th>
<th>( \lambda ) [µm]</th>
<th>Active region length</th>
<th>Publication</th>
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<tbody>
<tr>
<td>Fujitsu/ OITDA</td>
<td>AlGaInAs</td>
<td>50</td>
<td>25</td>
<td>BW &gt;20 GHz at 25ºC</td>
<td>DR 1.3</td>
<td>100 µm</td>
<td>40</td>
<td>OFC[49] 2009</td>
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<tr>
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<td>BW &gt;15 GHz at 50ºC</td>
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<td></td>
<td>BW &gt;9 GHz at 70ºC</td>
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<tr>
<td>Fujitsu/ OITDA</td>
<td>AlGaInAs</td>
<td>50</td>
<td>75 µm</td>
<td>BW &gt;20 GHz at 25ºC</td>
<td>DR 1.55</td>
<td>100 µm</td>
<td>75</td>
<td>LEOS[50] 2009</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>BW &gt;15 GHz at 85ºC</td>
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<tr>
<td>Fujitsu/ OITDA</td>
<td>AlGaInAs</td>
<td>50</td>
<td>100 µm</td>
<td>BW &gt;20 GHz at 25ºC</td>
<td>DR 1.3</td>
<td>100 µm</td>
<td>70</td>
<td>ACP[51] 2009</td>
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<td>BW &gt;11 GHz at 70ºC</td>
<td></td>
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<tr>
<td>Fujitsu/ PETRA</td>
<td>AlGaInAs</td>
<td>50</td>
<td>100 µm</td>
<td>28.3 GHz at 25ºC</td>
<td>DR 1.3</td>
<td>100 µm</td>
<td>85</td>
<td>ISLC[52] 2010</td>
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<tr>
<td>NTT</td>
<td>AlGaInAs</td>
<td>50</td>
<td>BW &gt;20 GHz at 25ºC</td>
<td>DFB (+WG) 1.3</td>
<td>100 µm</td>
<td>60</td>
<td>OFC[53] 2011</td>
<td></td>
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<tr>
<td>Fujitsu/ PETRA</td>
<td>AlGaInAs</td>
<td>50</td>
<td>25 GHz at 25 ºC</td>
<td>DR 1.3</td>
<td>100 µm</td>
<td>70</td>
<td>OFC[54] 2011</td>
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<td>19.4 GHz at 70ºC</td>
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<tr>
<td>Hitachi/ Oclaro</td>
<td>InGaAsP</td>
<td>50</td>
<td>150 µm</td>
<td>BW &gt;20 GHz at 20ºC</td>
<td>DFB 1.3</td>
<td>150 µm</td>
<td>55</td>
<td>OFC[55] 2013</td>
</tr>
</tbody>
</table>

Note: Modulation speeds are 40 to 45 Gbps

Tab. 1.5. Recent reports of above 50 Gbps direct modulation
Tab. 1.3 to Tab. 1.5 shows benchmark transmitters developed for 25/ 40/ 50 Gbps operation respectively. The active region length, material system, cavity type and emission wavelength is listed in the table. Moreover direct modulation bandwidth is listed in the tables with temperature to show the experimental direct modulation bandwidth at corresponding speed of operation.

1.2.3 Comparison between Regular LDs and Active MMI-LDs

A semiconductor laser with an active MMI cavity is one of the most promising broad area structure. In active MMI-LD pump section can be separated from modulation section, so the modulation section can be designed into a limited small area[60]. Active MMI offers regular single mode output without grating structure [61]–[63], which can be coupled into a standard single mode fiber without using an additional output mode trimming device. In order to produce a single-transverse-mode beam, the width of the active layer of the waveguide of the conventional LD is limited to about 2 to 4 μm. So the output level of an LD has so far been limited for technical reasons. But for active MMI-LD in spite of having very wide multi-mode optical waveguide, only high power single mode beam is generated at the facet by transforming all the higher order mode beams into a single mode beam[64]. Also the size, simplicity of fabrication, high fabrication tolerance, low series resistance[65], low voltage operation[65] and compact split modulation section makes it a promising candidate for short distance applications. Moreover the split pumping region let us avoid the pumping section’s parasitic capacitance affect on modulation performance. MMI integrated pumping region has a potential to deliver high photon density toward the modulation section compared to single regular stripe pumping region[66]. Approximately 1.7 times higher active area can be designed for a 315 μm long active MMI-LD. Larger active area helps to generate
higher photon density in the electrically isolated small modulation section and enhances the modulation bandwidth of specially designed active MMI-LD [67]. Moreover, in active MMI laser cavity, higher order modes are present, so the modulation bandwidth could be strongly enhanced well beyond the relaxation frequency by utilizing higher order modes to introduce photon-photon Resonance [28].

1.3 Outline of This Thesis

The introductory concept of high speed optical access network and state of art high speed laser diodes has already been reviewed in Chapter 1. The objective of this thesis is to enhance the modulation bandwidth and characterize the high speed performance of active multimode interferometer laser diode (active MMI-LD) for future high speed optical communication applications. To report the accomplished objective of this research work. The thesis is organized as follows:

In Chapter 2, the theory of small signal direct modulation of a semiconductor laser is examined and important figures of merits are identified.

Chapter 3 discusses the novel split pump concept for the active multimode interferometer laser diode. Following a device concept of split pump active multimode interferometer laser diode, the chapter describes significant enhancement of electrical to optical 3 dB down frequency bandwidth ($f_{3db}$). Reported high bandwidth for split pump active MMI-LD is around 3.5 times higher than the previously reported maximum 3 dB bandwidth of active MMI-LD without split pumping section [60], [68]. High speed large signal modulation characteristics are also presented in this chapter.
Chapter 4 discusses about the high intrinsic modulation bandwidth of active multimode laser diode. The strategy to enhance the modulation bandwidth of the asymmetric active MMI-LD has been presented for above 40 GHz operation. Extracted value of photon density for 40 GHz 3 dB bandwidth by direct modulation is also presented in this chapter[67], [69].

Chapter 5 discusses about the strategy to enhance the modulation bandwidth of the asymmetric active MMI-LD by exploiting photon-photon resonance for the first time[28], [70]–[72] and a record high modulation bandwidth for the case of active MMI-LD has been achieved [28], [73]. Verification of the relation between the second resonance peak present in the small signal modulation response with a value that corresponds the mode separation is presented. Moreover, the required design issues has also been presented for the realization of 100 GHz extended bandwidth.

1.4 References


Chapter 2  Theory of High Speed Modulation

2.1 Introductory Overview

Semiconductor lasers are widely used for data and optical communication as they can provide emission wavelengths which lie in the telecommunication window (1.55 & 1.3 μm). One of the requirements for such lasers is to be able to modulate at high speed so that higher data volume can be transmitted. In order to push the bandwidth of directly modulated laser, it is important to understand the theory that governs its dynamics. Therefore, in this chapter the dynamic properties of the laser will be discussed. It will also be shown how photon-photon resonance (PPR) takes place and what advantages it has. Finally we will see how the modulation bandwidth can be enhanced by utilizing carrier photon resonance (CPR) and photon-photon resonance (PPR) in active multimode interferometer laser diode.

2.2 Brief Overview of Semiconductor Laser Modulation Response

The small signal bandwidth of semiconductor lasers is commonly used as a predictor to their large signal modulation capabilities. So for high speed characterization of laser, it is of immense interest to understand their dynamic properties and characterize their small and large signal modulation response. A typical advantage of semiconductor laser is that they can be directly modulated converting a current signal with a frequency reaching tens of GHz into an optical form [1], [2]. Small signal modulation of a semiconductor laser is evaluated by adding a small sinusoidal current of frequency (f) to a DC injection current that operates the laser well above threshold [3], [4]. The response of the carrier and photon
density of the laser under steady state condition can be considered similar to the modulated current. Small signal modulation characteristics has been the subject of intensive experimental and theoretical studies for a considerable period of time [5]–[12]. It has been seen that the modulation bandwidth is determined by the relaxation frequency and damping rate of laser oscillation and increases with the bias current up to the saturation limit [13]. This ultimate maximum modulation frequency is a direct measure of the maximum speed or bit rate at which information can be transmitted by the laser.

The static and dynamic behavior of semiconductor lasers can be described by a set of rate equations that describe the dynamic photon number, optical phase and injected electron number [14]. Small-signal analysis solutions are commonly given in the frequency domain and from the solution of rate equation modulation transfer function can be derived, that eventually can lead us towards the estimation of intrinsic bandwidth of the laser diode. Measurement of relaxation oscillation frequency, damping coefficient, K-factor and intrinsic modulation bandwidth helps to obtain a good understanding of how the laser would work at high-speed modulation[15]. From the solution of rate equation, simplified modulation transfer function can be written as [3]:

\[
H(\omega) = \frac{\omega^2_{R}}{\omega^2_{R} - \omega^2 + j\omega\gamma} \cdot \frac{1}{1 + j(\frac{\omega}{\omega_p})}
\]  

(2.1)

Where \(\omega\) is modulation angular frequency, \(\gamma\) damping factor. Modulation transfer function presented in equation (2.1) can be rewritten in terms of frequency as:
Where \( f_p \) represent the parasitic roll of frequency of the laser diode and can be written in terms of resistance and capacitance for easy understanding of the parasitic impedance effect on the laser bandwidth. The modified form of equation (2.2) is shown in equation (2.3).

\[
H(f) = \frac{f_R^2}{f_R^2 - f^2 + j\gamma \frac{f}{2\pi}} \cdot \frac{1}{1 + j\frac{f}{f_p}}
\]

\[
(2.2)
\]

\[
H(f) = \frac{f_R^2}{f_R^2 - f^2 + j\gamma \frac{f}{2\pi}} \cdot \frac{1}{1 + j2\pi f CR}
\]

\[
(2.3)
\]

Where \( f_R \) represent resonance frequency, \( C \) in the capacitance of the laser diode and \( R \) represent the equivalent dynamic resistance of the laser diode.

### 2.3 Bandwidth Limiting Factors

From Eqs. (2.3), it is evident that the modulation transfer function is related to relaxation oscillation frequency, damping coefficient, capacitance and resistance of the laser diode. So the carrier photon interaction (CPR) related bandwidth limiting factor are mainly limited by the factor listed below:

- Relaxation oscillation frequency \( (f_R) \).
- Damping coefficient \( (\gamma) \)
- Parasitic impedance (CR time constant)
To understand those limiting factors, it is important to understand how they are related to dynamic parameters of the laser diode, and it is also important to understand the methodology to improve them by optimized way. To clarify that, an easy-to-understand chart is presented below:

Chart 2.1. Bandwidth enhancement methodology

To enhance the bandwidth of the laser diode, optimization of all the parameters is needed simultaneously. The general methodology to optimize those above-mentioned parameters are briefly summarized in next sections.
2.4 Methodology to Enhance Relaxation Oscillation Frequency

Most of the semiconductor laser diode show damped oscillation around threshold. This phenomenon of damped oscillation is termed as relaxation oscillations in lasers. It restricts the modulation frequency of laser diode and thus puts an upper limit on the bandwidth of the system based on that particular laser [16],[17]. The relation of the relaxation oscillation frequency and relaxation angular frequency with dynamic laser parameters are presented below. Simplified equation for the modulation angular frequency \((\omega_R)\) can be written as [3]:

\[
\omega_R^2 = \frac{v_g \frac{dg}{dN} \cdot \eta_i (I_{pump} - I_{th})}{q \tau_p} \tag{2.4}
\]

Where \(v_g\) is group velocity, \(\frac{dg}{dN}\) is variation of carrier density, \(q\) is electron charge, \(\tau_p\) is photon lifetime, \(\eta_i\) is internal quantum efficiency, \(I_{pump}\) is the pump current and \(I_{th}\) is the threshold current of the laser diode. Equation (2.4) can be represented in terms of relaxation oscillation frequency as Eqs. (2.5).

\[
f_R^2 \approx \frac{v_g \frac{dg}{dN} N_p}{4 \pi^2 \tau_p} \tag{2.5}
\]

Where, \(N_p\) is photon density inside the laser cavity, \(v_g\) is group velocity and \(\tau_p\) is photon life time. In another representation the simplified equation of the relaxation oscillation frequency \((f_R)\) can be written as:
\[ f_R^2 \propto \frac{\Gamma \frac{dg}{dn}}{LWN_wL_w} (I_{pump} - I_{th}) \]  

(2.6)

Where \( \Gamma \) is optical confinement factor, \( \frac{dg}{dn} \) is differential gain, \( L \) is length of the active gain region, \( W \) is the width of the active gain region, \( N_w \) is the number of quantum well and \( L_w \) is the thickness of quantum well. The frequency at which the electrical power response drops to half of the value is known as 3 dB bandwidth of laser \( (f_{3dB}) \). Once the signal drops well below 3 dB, data cannot be transmitted efficiently. The bandwidth of the laser explicitly depends on the resonance frequency of the laser diode \( (f_R) \). As mentioned earlier in section 2.3 and Eqs. (2.3), the 3dB bandwidth of the laser diode is related to and limited by the maximum relaxation oscillation frequency. Theoretically the 3dB bandwidth of a damping free, parasitic free semiconductor laser under direct current modulation is 1.55 times of the maximum relaxation oscillation frequency, as shown in Eqs. (2.7). In practical case the damping and parasitic capacitance render the bandwidth \( (f_{3dB}) \) always smaller than 1.55\( f_R \).

\[ f_{3dB} = 1.55 f_R \]  

(2.7)

From above mentioned equations it is evident that in order to increase the relaxation oscillation frequency three important dynamic parameter need to be optimized. The parameters are listed below:

- Reduction of photon lifetime.
- Enhancement of differential gain.
- Enhancement of photon density.
To better understand optimization and subsequent effect of optimization of the above mentioned parameters, further brief discussion has been included in following subsections.

2.1.1 Reduction of Photon Lifetime

Reducing the photon lifetime ($\tau_p$) by reducing active region volume hence decrease of length (L) and width (W) can decrease the photon life time effectively. Such a laser has to be driven at higher current densities and thermal effects due to excessive heating must be considered to avoid the limitation of maximum attainable modulation bandwidth [17]. But reduction of thickness of the active area by reduction of the thickness of quantum well ($L_w$) and by reduction of number of quantum well ($N_w$) decreases optical confinement factor ($\Gamma$) and consequently compensate the benefit of thickness reduction.

One critical problem of reducing active volume is, it increases the threshold gain. Also due to non-optimized and/or excess reduction of length, reduces the differential gain of the laser. To overcome the problem optical confinement needs to be increased. Comparatively large number of quantum well is needed to increase the optical confinement for this purpose. Another way to compensate is by increasing the optical feedback of reflectors. High reflection (HR) coating, integrated mirror or large coupling coefficient of grating can improve the optical feedback condition [18]. Another difficulty related to length reduction is the cleaving of the laser diode [19]. Under 200 $\mu$m length cleaving becomes difficult. To overcome this issue commonly passive sections are integrated with the active section to increase the total length above critical length needed for easy cleaving [19]. In
active MMI-LD the length of the laser is reasonably short (315 µm) and the enhanced photon density can be even more beneficial in such short length design [15].

2.1.2 Enhancement of Photon Density and/or Deferential Gain

Enhancement of Deferential Gain

Malarial properties like, large conduction band offset ($\Delta E_c$) and small valence band offset ($\Delta E_v$) can enhance the optical confinement of the laser diode. As the optical confinement is directly proportional to the differential gain so consequently the differential gain can be improved [20]. Another way of enhancing the differential gain is to utilize the concept of detuning of laser wavelength. Difference between the lasing wavelength ($\lambda_{Laser}$) and gain peak of wavelength ($\lambda_{Gain}$) is called detuning and it can increase the differential gain of the laser [21]. Generally shorter lasing wavelength ($\lambda_{Laser}$) than peak of gain wavelength ($\lambda_{Gain}$) of laser can provide larger differential gain ($dg/dn$). The wavelength detuning also depends on the temperature, so optimization is needed to support higher differential gain at all temperature. Optimum number of quantum well [22] and thinner quantum well should be chosen to achieve higher differential gain [23]. Significant enhancement of differential gain using strained quantum well along with doping has also been reported [24][25]. In case of active MMI-LD strained multiple quantum well (MQW) has been used in order to obtain a high material gain.
● **Enhancement of Photon Density**

Apart from enhancing the differential gain, photon density \(N_p\) can be increase in the modulation section of multi-section laser by electrically splitting the modulation section from the pump section and using specially designed short structure like active multimode interferometer section to deliver higher photon density in the modulation section. Which will be discussed in later chapter in more detail.

### 2.5 Methodology to Optimize Damping

From Eqs. (2.8) and (2.9), the intrinsic damping limitation can be found. The relaxation oscillation frequency increases as the photon density is increased, but the damping \(\gamma\) is also increased. Since the damping increases faster than the relaxation oscillation frequency \(f_R\), so the damping will eventually limit the system. This means that the maximum intrinsic 3 dB bandwidth is set by the K-factor and damping coefficient offset \(\gamma_0\).

\[
\gamma = Kf_R^2 + \gamma_0
\]  
(2.8)

Where, \(\gamma_0\) is the damping coefficient offset of laser diode.

\[
K = 4\pi^2\tau_p \left[ 1 + \frac{\Gamma(dg/dN_p)}{(dg/dN)} \right] \frac{\gamma}{f_R^2}
\]  
(2.9)

Where, \(dg/dN_p\) is the variation of photon density inside laser cavity.
Generally, the laser has a flat response at low frequencies, rise to a peak near relaxation oscillation frequency \( f_R \) and then roll off at high frequencies. The prominence of the relaxation peak is determined by the damping factor \( \gamma \), with a small damping factor resulting in a large, narrow peak and a large damping factor resulting in a small, broad relaxation peak. Looking at Eqs. (2.8), we see that the damping factor can be expressed in terms of the relaxation oscillation frequency. For smaller currents, the ratio of \( \gamma/\omega_R \) is less than \( \sqrt{2} \) and the laser is said to be under-damped. In this regime, there is a peak in the response near the relaxation frequency. After the relaxation peak, the response falls off sharply, limiting the bandwidth of the laser. As the current is increased, the bandwidth also increases until the ratio of \( \gamma/\omega_R \) is equal to \( \sqrt{2} \). At this point, the laser is said to be perfectly damped and the maximum possible bandwidth can be achieved. As the current is further increased the laser becomes over-damped causing a more gradual roll-off that reduces the useable bandwidth [3]. So to optimize the available bandwidth of the laser damping factor should be optimized.

As indicated before, intrinsic modulation bandwidth of the semiconductor laser depends on K-factor of laser and related to the damping coefficient. Damping in laser diode suppresses the frequency responses by nonlinear effect. To keep the K-factor low to optimize the damping and subsequently achieve higher possible 3 dB bandwidth, three factors need to be considered.

- Optimization of nonlinear property of gain material.
- Higher photon density.
- Shorter photon life time.
As the photon density and shorter life time is also common for the enhancement of relaxation oscillation frequency. So nonlinear property should be specially taken care to avoid the over or under damp condition.

2.6 Methodology to Optimize Parasitic Bandwidth Limitation

In most cases, the parasitic response is determined by the RC time constant associated with the chip’s contact-layer resistance and the contact-layer capacitance [12]. Parasitic impedance limit the modulation bandwidth by acting as an electrical filter. The combination of parasitic resistance and capacitance form a RC time constant and the electrical bandwidth of the laser depends on that. The resistance and capacitance of the laser diode should be kept low and any reduction in either of these quantities leads to significant improvements in the parasitic response.

Resistance of the laser diode increases with the reduction of the active length of the laser gain medium [26]. Generally, Optimization of the cladding layer doping profile decreased band discontinuity and optimized doping in hetero structure interface along with reduction of contact pad resistance can lower the resistance of the laser diode. In case of MMI-LD the larger active area with shorter length can naturally provide lower differential resistance as low as $1\Omega$ [27]. On the other hand the capacitance is almost independent of design of active layer and cavity. Using reduced area of upper cladding area by current blocking layer and designing small bonding pad can lower the capacitance of the laser diode.

During high speed experiment normal transmission line effects become a concern. The basic consideration for proper transmission of high-speed pulses is to maintain a
controlled impedance for the system in our case the transmission line characteristics impedance is 50Ω. To maintain sharp pulse waveforms with low raise time and fall time at the laser diode, the signal cable carrying high frequency signal to the laser diode must be properly terminated. Reflections due to a load mismatch at the pulse pattern generator (PPG) end will not be absorbed by the source impedance, but will rather be re-reflected. Due to the impedance mismatch a standing-wave pattern on the transmission line appears, which cause distortion and even can damage the laser. Since the dynamic impedance of active MMI laser diode is typically much smaller than 50Ω, a matching network must be used for high speed large signal modulation characterization. In its simplest form this can be a series resistor whose value is equal to the difference between 50Ω and the dynamic impedance of the active MMI laser diode. The designed active MMI-LD showed a dynamic resistance of 2.6 Ω. So 47.4Ω series resistor is an ideal value of resistance for basic impedance matching. The power rating of this resistor must be adequate to handle the maximum current at the duty cycle that is expected to be delivered by the system. In case of active MMI-LD power rating should be chosen around 1W to safely operate the laser at maximum allowed current rating. Also, the resistor should be low inductance so a small chip resistor (surface mount type) or metal film type is an excellent choice. The impedance of a laser diode is complex by its nature, non-linear and changes with signal frequency so any matching will apply to specific conditions. On top of resistive matching, additional matching may be required if the diode has a significant reactive component. The capacitance added to the diode must be minimized. If the cathode is connected to the laser mount, optical table, and earth ground, then the parasitic capacitance between these structures will cause slow rise times. This slow raise time will cause speed limitation and also make repeatable results difficult. To minimize
this capacitance effect, it is desirable to have very little conductive surface connected electrically to the laser, preferably the cathode should not be connected to the signal generator through heat sink or mount [28].

2.7 Photon-Photon Resonance

As discussed in previous sections, conventional laser bandwidth is limited by its material properties, photon density, photon lifetime, differential gain. So far discussion about the bandwidth enhancement had been limited to higher current, making devices smaller to have a reduced volume, decreasing the photon lifetime by anti-reflecting coating or by having a higher differential gain and increasing photon density by using electrically isolated pump section. But still a significant enhancement in modulation characteristics are desirable and substantial efforts have been undertaken to increase the direct modulation bandwidth of laser through various methods. To overcome the intrinsic limitations of the laser diode, one of the promising approach along with the previously mentioned optimization is exploiting higher order resonances such as the photon-photon resonance (PPR) [29]–[33].

Photon-photon resonance is caused by the revolution of a photon within the multimode section of active multimode interferometer laser diode[34]. In conventional high speed short cavity lasers, the PPR has no impact on the high-frequency response characteristics because the frequency distance between the two resonances is too large to get a coupling between CPR and PPR [31]. So in order to couple the CPR with PPR to enhance the bandwidth, the CPR must be extended as much as possible and the PPR is
brought close enough. If the PPR occurs before the response from CPR drops below -3 dB, the two resonances can be effectively coupled together to significantly enhance the bandwidth (Fig. 3.3 [55]). When two electromagnetic waves having the similar amplitude but slightly different wavelengths \((\lambda_1 - \lambda_2)\) interfere, a second resonance peak corresponding to the mode separation \(\Delta \lambda = (\lambda_1 - \lambda_2)\) appear in small signal modulation response of the directly modulated laser diode[31], [35]. As these two photon belong to two slightly different wavelengths, their interaction is known as photon-photon resonance. In active multimode interferometer laser diode wide multimode section behind the tiny electrically isolated modulation section can be designed to enhance the photon density in short cavity laser to boost up the CPR and due to presence of multiple mode inside the pump section PPR can be induced to extend the modulation bandwidth further, which will be discussed in more detail in chapter five.

2.8 References


Chapter 3  Split Pump Region in Active Multimode Interferometer Laser Diode for Bandwidth Improvement

3.1  Introductory Overview

As we discussed in chapter one that laser diode capable of high speed direct modulation is one of the key solution for short distance applications due to their low power consumption, low cost and small size features. So realization of high modulation bandwidth for direct modulated laser maintaining the above mentioned feature is needed to enhance the short distance low cost data transmission. Also in chapter two we discussed about the enhancement method to extend the bandwidth of the directly modulated laser diode. Eventually, one promising approach to enhance the modulation speed is to increase the photon density in the modulation section to achieve high modulation bandwidth. So to achieve this target 1.55-μm InGaAsP/InGaAsP Multiple quantum well (MQW) asymmetric active Multi Mode Interferometer Laser diode (MMI-LD) has been demonstrated. The split pumping concept has been applied for the active multi-mode interferometer laser diode (active MMI-LD) [1]. In addition to the existing bandwidth enhancement schemes described in chapter two, this chapter describes newly proposed additional approach namely split pumping region in active multimode interferometer (active MMI). As pumping region is separated from modulation section, so the modulation section can be designed into limited small area. A semiconductor laser with an active MMI cavity is one of the most promising broad area structures. Active MMI offers regular single mode output, which we coupled into a standard single mode fiber without using an additional output mode trimming device.
The experimental verification of the split pump concept and subsequent bandwidth enhancement is presented in this chapter. As we described in chapter two, the relaxation oscillation frequency depends on the photon density. At the same time, the bandwidth of the laser is proportional to the relaxation oscillation frequency. So significant enhancement of electrical to optical 3 dB down frequency bandwidth \( f_{3dB} \) up to 8 GHz has been achieved using the scheme. The experimental result shows significantly higher bandwidth than previously reported bandwidth (2.3 GHz) without the split pump scheme. The above mentioned enhancement of bandwidth due to the enhancement of resonance frequency has been experimentally verified and reported in detail in this chapter. After this characterization, the threshold current density \( J_{th} \) and resonance frequency enhancement factor \( \eta f_R \) has been extracted from the experimental result and those result showed good potentiality for high speed large signal modulation. So finally, the lager signal modulation of the designed active MMI-LD has been experimentally evaluated and presented in this chapter. The device showed clear and open eye diagram for 2.5 Gbps, \((2^7-1)\) pseudo random bit sequence (PRBS) modulation [2]. Those experimental results indicate the clear potentiality of the active MMI-LD as direct modulation light source.

3.2 Scope of Split Pump Scheme

Direct modulation through the variation of the laser diode's injection current is one of the means whereby electronic data is transferred onto the optical carrier. Recently, researchers concentrated on direct modulation laser diode especially for short distance application [3] such as radio over fiber [4], short distance optical interconnects [5] and on-chip photonic network [6]. Over the past decades, substantial efforts have been undertaken
to increase the direct modulation bandwidth of semiconductor laser through various methods. Among them, injection locking [7], utilization of photon-photon resonance (PPR) [8], [9], Push-pull modulation [10], [11], Multiline interface [12] and short cavity scheme [13] has been proposed and demonstrated so far. The problem with the short cavity design is the chip resistance increases and this leads to the likelihood of self-heating. For this reason, when the cavity is short, relaxation oscillation frequency \( f_R \) levels off at a high injection current and high operating temperature [3], [14]. In the case of optical injection-locking (OIL), the output power level and wavelength of an injection-locked slave laser are mainly determined by the master laser. The requirement of strong injection power together with practical limitations such as heating and gain compression limits the performance of modulation [7]. In order to increase the 3-dB modulation bandwidth by exploiting the PPR effect, a careful structure and operating regime analysis has to be carried out even when the PPR is available. Parasitic damping mechanisms and a flat modulation response between

![Diagram](image)

Fig. 3.1. (a) Active MMI-LD with split pump configuration (b) Conventional laser
the CPR and PPR are critical issues in exploiting the PPR for enhanced modulation bandwidth [15]. In this case, active MMI-LD is a promising structure because one of the basic prerequisite to exploit the PPR is presence of multimode inside the laser cavity. Split pump active MMI-LD can easily ensure that multimode interaction requirement. Detail condition for achieving the PPR and subsequent enhancement is presented in chapter five. Because of the complexity and limitation of most of the above mentioned methods, semiconductor laser with enhanced direct modulation capability and suitable for short distance communication application is widely researched. One promising approach to enhance the modulation speed is to increase the photon density into the cavity [1], [2]. Fig. 3.1(a) shows the split pump concept. In the picture, multimode section is connected to the tiny modulation section and as the width of the modulation section is approximately 1/3 of the pump section width. So all the photon generated due to the spontaneous emission process inside the wider pump section must pass through the narrow modulation section. This above mentioned process eventually increases the density of photon in modulation section. In conventional laser diode the width of the laser must be kept narrow (2μm - 4μm) to avoid multiple transverse mode emission from the laser. So only a small amount of current can be injected in the active area. That restricts the maximum photon density and power of the laser [16]. The benefit of having self-imaging in active MMI-LD contributed towards the integration of multimode section with the single transverse mode waveguide to achieve higher photon density avoiding multimode emission. To show the above mentioned advantage of split pump section, a conventional laser with comparative photon density is schematically shown in Fig. 3.1(b).
Laser parasitic cutoff frequency is not fixed but shifts toward lower frequencies with increased bias even with constant parasitic capacitance and lesser series resistance and limit the maximum attainable modulation bandwidth of the laser [17]. So to improve this situation the contact area of the laser’s modulation section should be small to avoid the parasitic limit. In this regard by utilizing split pumping region in active multi-mode interferometer (active MMI), modulation section can be designed into limited small area. As mentioned before, the capacitance of laser device adversely affect the larger signal modulation performance. So the electrically splitting the pump section isolates the pump section parasitic effect on modulation performance as shown in Fig. 3.2. That only leaves behind the benefit of higher photon density without the effect of parasitic impedance of pump section.

3.3 Design and Fabrication of Split Pump Active MMI-LD

Fig. 3.2. Electrically isolated pump section of active MMI-LD
separated from modulation region, is consisted of MMI waveguide that enables to emit larger optical power compared to single stripe waveguide [18]. The MMI, which enables the single-mode optical field at the input to be identically imaged at the MMI output [19],

Fig. 3.3. (a) Microscopic view of fabricated active multimode interferometer laser diode. (b) Schematic view of actually implemented asymmetric active multimode interferometer laser diode.
has a wider area than the single-mode waveguides. The larger active area contributes to the reduction of series resistance, enhance output power [20] and also results a significantly lower driving voltage [21]. The possible photon density in the modulation region is enhanced significantly from this MMI configuration. The designed MMI consists of asymmetric 1×1 MMI Coupler with both port connected to single mode high mesa waveguide. For the actual implemented devices, the total length of the cavity was 315 µm. The MMI section width was set to 8 µm. The length of the MMI section was 133 µm and with both edges connected to a 2 µm oppositely off-centered single mode waveguide of 3 µm width. The length of the pumping section was set to be 265 µm and the modulation section was set to be 50 µm. The device geometry and layer structure is illustrated in Fig. 3.4 (a) and Fig. 3.4 (b). The high mesa asymmetric configuration ensures single wavelength characteristics [22]. For the actual implemented device, 7 layers InGaAsP/InGaAsP multiple quantum well (MQW) active layer has been used in order to obtain a high material gain. The multiple quantum wells (MQW) consist of undoped-InGaAsP wells separated by InGaAsP barriers, sandwiched between 90 nm thick (λ = 1.15 µm) InGaAsP optical confinement layers. The side wall of the high mesa waveguide is exposed to polyimide material. To realize the high mesa waveguide, we etched down the waveguide structure by using the RIE (Reactive Ion Etching) and stopped at a mesa height of 3.019 µm. Compressive strain of the quantum well was +0.85%, barrier energy was 1.07 eV, thickness of barrier was 10 nm, the thickness of well was 5.5 nm and the thickness of the cladding InP was 1500 nm. Separate contact pad had been constructed for the modulation section and the pumping section. In actual device gold ware used as top contact pad material. The fabricated active MMI-LD emits at 1550 nm band. Length of the fabricated laser is 315 µm
and other dimension are presented in the schematic diagram (see Fig. 3.3(b)). The calculated active area for the length of 315 µm is $(1.61 \times 10^{-9} \text{m}^2)$. Whereas for a regular LDs with similar 3 µm width waveguides and the same cavity length, the active area is $9.45 \times 10^{-10} \text{m}^2$. Consequently 1.7 times higher active area in active MMI-LD helps to generate higher photon density in the electrically isolated small modulation section and enhances the modulation bandwidth of specially designed active MMI-LD. Using this new approach, experimentally validated enhanced 3 dB bandwidth with back to back modulation performance has been presented in this chapter. Significantly higher carrier photon resonance related modulation bandwidth $(f_{3\text{dB, CPR}})$ of 8 GHz has been achieved for active multimode interferometer laser diode.

![Layer structure of active MMI-LD](image)

Fig. 3.4. Layer structure of active MMI-LD (a) Side view (b) Front cross sectional view.
High resolution broadband optical spectrum analyzer (OSA) has been used to measure the optical spectrum of the fabricated laser diode. The laser output has been coupled to a single mode anti-reflection coated lanced fiber for measurement. Optical isolator is also used to avoid unintended reflation back to laser diode. Measurement has been carried out at room temperature (RT, 25°C). The temperature was controlled and kept constant during the measurement using thermoelectric cooler. The active MMI-LD successfully produced CW single wavelength emission at RT as shown in Fig. 3.5. The single wavelength output has been produced by suppressing Fabry Perot mode due to the asymmetric configuration of port for different pump currents [22]. The measurement has been carried out for different pump section current ranging from 80 mA to 120 mA. Obtained results are superimposed.

### 3.4 Emission Spectrum of Active MMI LD

Fig. 3.4. Layer structure of active MMI-LD (a) Side view (b) Front cross sectional view.
in a single plot and presented in the following figure. The fabricated device is non grating and does not need any complicated regrowth stages during fabrication to achieve single wavelength emission. It is evident from that an average value of side mode suppression ratio is around 25 dB for the above mentioned operating current range. The measured SMSR is a good indication of compatibility as a direct modulation source.

![Graph showing Emission spectrum of asymmetric active MMI-LD at different pump section currents.](image)

Fig. 3.5. Emission spectrum of asymmetric active MMI-LD at different pump section currents.

The difference of power between center peak longitudinal mode with the nearest higher order mode is called side mode suppression ratio (SMSR) and an important
parameter to evaluate direct modulation laser performance. The obtained side mode suppression ratio (SMSR) for the implemented active MMI-LDs at pumping current of 120 mA was around 30 dB. The side mode suppression ratio (SMSR) has been measured for all currents in the range mentioned before in a 20 mA steps. The measured result has been presented in Fig. 3.6. An average value of SMSR around 25 dB has been found. Which is a good indication as a direct modulation source.

3.5 Enhanced Bandwidth Split Pump Active MMI-LD Under Direct Modulation

Having discussed the basic theory behind the laser modulation response and the significance of the relaxation frequency and damping factor and single wavelength emission
spectrum, next section is dedicated for the experimentally determined modulation performances. The most straightforward method to evaluate the modulation capability of a directly modulated laser is to impose a small modulation signal on the DC drive current of the laser under test and measure the small signal response of the laser diode. The RF output of the network analyzer is combined with the DC laser drive current by using a bias source in bias port of the network analyzer. The injection current is controlled from that driver. The resulted signal is injected in the laser. The laser itself is held at a constant temperature of 25°C by a thermoelectric cooler and the optical output is coupled into optical fiber using a lensed fiber tip. The output of the laser is sent to a flat response high frequency sensitive photodetector through an optical isolator to prevent reflections back in to the laser cavity. The RF output of the photodetector is sent back to the vector network analyzer (VNA).

![Graph](image-url)

**Fig. 3.7.** Bias dependent small signal modulation response of split pump active MMI-LD with 5 mA modulation section current.
Finally, the frequency response of the laser can be found by sweeping the frequency of the small signal modulation up to desired high frequency measurement window. As the response of the laser depends on the injection current in the pump section, so the measurement has been carried out for several pump current value until the bandwidth saturates. The measurement was carried out keeping the modulation section current fixed at 5 mA without impedance matching and the experimental results of small signal modulation response are shown in Fig. 3.7. The response indicates that the resonance frequency increases with the increasing pumping section current, which was well expected and confirmed for the designed active MMI-LD. At and above pump current of 120 mA the carrier photon resonance (CPR) peak become relative flat and no further 3 dB bandwidth improvement was observed with higher injection current and we did not observe any strong damping up to 8 GHz of measurement window. Resonance frequencies and 3 dB bandwidths are also summarized in Table 3.1.

Table 3.1. Small signal response of active MMI-LD

<table>
<thead>
<tr>
<th>Pumping Section Current</th>
<th>Resonance Frequency</th>
<th>3 dB Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 mA</td>
<td>1.6 GHz</td>
<td>2.3 GHz</td>
</tr>
<tr>
<td>80 mA</td>
<td>3.8 GHz</td>
<td>5.1 GHz</td>
</tr>
<tr>
<td>100 mA</td>
<td>4.9 GHz</td>
<td>6.2 GHz</td>
</tr>
<tr>
<td>120 mA</td>
<td>5.8 GHz</td>
<td>8 GHz</td>
</tr>
</tbody>
</table>
It shows the maximum 3 dB bandwidth was 8 GHz, evaluated for 120 mA pumping current. The table also summarize the increasing trend of resonance frequency and 3 dB bandwidth. Resonance frequency as a function of square root of current above threshold is plotted in Fig. 3.8, where $I_{th}$ represent threshold current of the pumping section and $I_{Pump}$ represent the pump section current value. The active MMI-LD sample used for the measurement had a threshold current ($I_{th}$) value of 52 mA. The measurement had been carried out for 60mA to 120mA in a 20mA steps. The bandwidth and resonant frequency increases in proportion to the square root of the current above threshold. That superior behavior of the split pump scheme for active MMI-LD was expected from the conventional rate equation analysis. Due to having large multimode wide pumping region behind the single mode output port waveguide and split modulation section, the photon density in the modulation section was increased, which enhanced the carrier photon resonance (CPR)

![Graph showing resonance frequency as a function of square root of current above threshold](image)

**Fig. 3.8.** Resonance frequency as a function of square root of current above threshold.
frequency characteristics of the laser. The threshold current density of the designed asymmetric active multimode laser was $J_{th}=3.5 \text{ KA/cm}^2$. The slope of the resonance frequency is also extracted from Fig. 3.8. The value of the resonance frequency efficacy factor is $0.55 \text{ GHz/mA}^{1/2}$. Those value also shows good potentiality for high speed modulation.

### 3.6 Transmission Characteristics of Direct Modulated Active MMI-LD

Fig. 3.9 illustrates the eye diagrams of the fabricated device. Electrical signal form the pulse pattern generator (PPG) was supplied to the laser modulation section using a SMA cable terminated to the laser mounting. Bias-T was connected in between the laser and SMA cable. The mounting was wire bonded to the modulation section of the laser. The modulation voltage swing was $2V_{PP}$ (Peak to peak) and dynamic extinction ratio was over 3.5 dB. Non return to zero (NRZ) signal was used for the modulation. The optical output power from the modulation section was about $9.61 \text{ mW}$ at a pumping section current ($I_{pump}$) of 120 mA and a modulation section current ($I_{m}$) of 5 mA. The modulation signal was 2.5 Gbps for a $2^7-1$ pseudorandom binary sequence (back to back). Output of the asymmetric active MMI-LD was coupled to an antireflection coated lance fiber. An isolator is also connected to cut any reflection back to the laser and finally the isolator is connected to broadband oscilloscope to observe the large signal modulation. The clear and symmetrical eye diagram shown in Fig. 3.9 has been confirmed for 2.5 Gbps operation. During measurement 50 $\Omega$ termination was used without impedance matching. Also no external filter was used to suppress noise. Small jitter is visible in the output which is not significantly large. Also no overshoot is observed. The small difference between the raise time and the fall time might be due to the
parasitic capacitance of the device. So the obtained result shows the potential of this device in optical communication systems. Obtained experimental 3 dB bandwidth is theoretically enough to achieve 10 Gb/s operation with clear eye opening, but for the longer pattern of PRBS or higher modulation speed, eye opening deteriorates and extinction ratio falls below 3 dB. As the research is ongoing, so the optimum experimental setup for achieving 40 Gbps operation is undergoing. We hope, after upgradation of the pulse pattern generator (PPG), photo detector, light coupling, radio frequency (RF) signal injection in the modulation section, 10 Gbps clear eye diagram with longer pattern length can be realized. In this design, we used overly large contact electrode pads for modulation, which increased the capacitance of our device. In chapter five a new improved electrical pad design is presented. Enhancement of modulation speed with much clear eye pattern may be achievable with improved and low capacitance modulation section and pumping section design. In future reduction of parasitic impedance and impedance matching using micro strip line may also improve the modulation performance of the active MMI-LD. Since the CPR induced
relaxation oscillation frequency \( f_{R,CPR} \) can be increased by increasing the photon density. So the above mentioned approaches combined with the photon density increment may lead towards 40 Gbps operation of asymmetric active MMI-LD. Consequently, to achieve over 40 GHz modulation frequency for 40 Gbps operation, it is obvious to enhance the active area in MMI pumping region. In future, the enhanced and optimum size active area may easily produce enough photon density in modulation section to successfully achieve 40 GHz carrier photon relaxation oscillation frequency \( f_{R,CPR} \).

3.7 Summery

In this chapter split pumping concept for active MMI-LD with enhanced frequency response is presented. More than 5.8 GHz resonance frequency with 8 GHz 3 dB bandwidth and clear eye diagram at 2.5 Gbps for a \( 2^7 \)-1 pseudorandom binary sequence had been demonstrated indicating the potentiality of this laser as directly modulated light source.

3.8 References


Chapter 4  High Intrinsic Modulation Bandwidth
Asymmetric Active Multimode Interferometer Laser Diode

4.1 Introductory Overview

The advance in laser bandwidth makes direct modulation a possible scheme for high-speed applications [1]. However, the maximum bandwidth for a free-running laser is limited by the K-factor [2]. As investigated in chapter three, the carrier photon related 3dB bandwidth of the laser was around 8 GHz [3]. Therefore intrinsic limits based on resonance frequency, damping and K-factors need to be analyzed to understand the limiting factors. When operating at high bit rates, Parasitic impedance of a semiconductor laser from extrinsic parasitic elements, such as submount, transmission line or bonding wires are very critical, because it may degrade frequency response due to parasitic elements. The parasitic network produces a high frequency roll off in the small signal response of the intrinsic laser. So study of the effects of parasitic is needed to understand the ultimate intrinsic performance of laser diode [3]. That is why the measurement of Intrinsic frequency response of a laser diode is important since it offers the upper limitation of the bandwidth of a laser diode and provides useful information about active region and values of some critical parameters [4],[5]. To measure the intrinsic modulation bandwidth of the laser diode several techniques have been proposed and used to eliminate the parasitic contribution to dynamic response, such as relative intensity noise measurements [6], frequency response subtraction[4], [7] three-pole transfer function fitting [8]. T-Matrix formalism [9]. Optical modulation method[5] and intermodulation distortion analysis method [10]. All these methods are
somewhat efficient to extract the intrinsic properties of the laser. Thus to realize active MMI-LD with higher modulation bandwidth, 1.55 µm InGaAsP/InGaAsP multiple quantum well (MQW) asymmetric active multimode laser diode (active MMI-LD) with split pumping scheme has been evaluated under small signal modulation and intrinsic modulation bandwidth has been extracted using three pole transfer function fitting for the active MMI laser structures and presented in this chapter. The modulation traces are analysed with a complete rate equation model that allows extraction of the resonance frequency and damping that are intrinsic to the carrier and photon processes occurring in the laser active region. This analysis enables calculation of the K-factor and corresponding intrinsic responses of the laser diode. It is found that extrinsic electrical issues rather than intrinsic factors currently constrain the maximum bandwidth of directly modulated active MMI-LD. By utilizing the split pump configuration in the designed active MMI-LD, high intrinsic 3 dB modulation bandwidth of 24.6 GHz is achieved [11]. To the best of our knowledge this is the highest reported intrinsic modulation bandwidth for active MMI-LD. Required photon density to achieve more than 40 GHz 3 dB bandwidth for direct modulation is also clarified in this chapter.

4.2 First Significant Intrinsic Modulation Bandwidth Improvements

Vector network analyzer (VNA) has been used to measure the small signal modulation characteristics ($S_{21}$) of the fabricated active MMI-LD. The active MMI-LD successfully produced CW single wavelength emission at RT due to asymmetric configuration[12] and produced around 9.61 mW output power at 120 mA of pump current ($I_{\text{pump}}$) and 5 mA of modulation current ($I_m$). The laser output has been coupled to a single
mode anti-reflection coated lanced fiber for measurement. Measurement has been carried out at room temperature (RT, 25°C). The temp was controlled and kept constant during the measurement using thermoelectric cooler. The small signal modulation characteristics ($S_{21}$) were evaluated under CW bias condition with a 65 GHz vector network analyzer (VNA), a bias-T, and a 65 GHz flat response photodiode. The measurement were repeated for various pump current ($I_{\text{pump}}$) ranging from 80mA to 130mA. To eliminate the test fixture errors, measured response was calibrated for the losses up to the reference point due to cables connectors and bias network using 12 term error correcting technique [13], [14]. The full two-port error model includes six terms for the forward direction and six terms (with different data) for the reverse direction for a total of 12 error terms [15]. Laser emission was focused by an anti-reflection (AR) coated lensed fiber and an optical isolator between

Fig. 4.1. Measured small signal modulation response ($S_{21}$) at different pump currents
the lensed fiber and detector has been employed to reduce the reflection back to the laser [16],[17] and eliminate the small ripples in the modulation response that sometimes occur due to optical feedback. The dc current level was provided by the internal bias-T, while the modulation frequency was swept up to 6 GHz at an intervals of 19.9 MHz steps with constant power. The measured modulation response of the laser beam is presented as a function of the modulation frequency and the pump current. Obtained results are superimposed in a single plot and presented in Fig. 4.1. The measured relaxation oscillation frequency \( (f_R) \) of the active MMI-LD was recorded 4.2 GHz at pumping current fixed at 130 mA. Threshold current of the pumping section was 65 mA when the modulation current was 5 mA. To calculate the threshold current density and the pump current density of the active

![Graph](image)

**Fig. 4.2.** Measured small signal modulation response \((S_{21})\) at different pump currents (shown as points). Solid lines are fits using the three pole modulation transfer function.
 MMI-LD the pump section area and the modulation section active area has been calculated from the schematic diagram shown in Fig. 3.3 (b) and the threshold current density and pump current density has been calculated. Threshold current density ($J_{th}$) was 4.45 KA/cm$^2$ for the pumping section and the modulation current density was 2 KA/cm$^2$. Fig. 4.4 shows the increasing trend of 3 dB bandwidth with the increment of square root of pump current above threshold. The modulation current efficiency factor (MCEF) which is related to the fundamental device properties (internal quantum efficiency, modal volume and differential gain)[18] has been extracted from the slope of the 3 dB bandwidth versus the square root of the current above threshold ($I_{pump} - I_{th}$)$^{1/2}$. Where $I_{th}$ represent the threshold current of

Fig. 4.3. Measured 3 dB bandwidth as a function of the square root of the current above threshold. Dashed line are linear fit for MCEF factor extraction.
the pump section and the $I_{pump}$ represent the pump section current value. Modulation current efficiency factor can be expressed as\[19\]

$$MCEF = \frac{f_{3dB}}{(I_{pump} - I_{th})^{1/2}}$$ (4.1)

The value of MCEF has been extracted by fitting above MCEF equation (Eqs. (4.1)) with the 3 dB bandwidth plot shown in Fig. 4.4. Extracted value of MCEF was 0.7 GHz mA$^{-1/2}$. Increasing trend of relaxation oscillation frequency ($f_R$) of the active MMI-LD with the increment of square root of pump current above threshold $(I_{pump} - I_{th})^{1/2}$ is presented in Fig. 4.4. The cross marker represents the experimental values of relaxation oscillation frequency.

![Graph](Fig. 4.4. Measured resonance frequencies as a function of the square root of the current above threshold. Dotted line are linear fit for D-factor extraction.)
frequency ($f_R$). A figure of merit commonly used to evaluate how efficiently an intrinsic laser can be modulated is the D-factor which can be expressed as [20]

$$D = \frac{1}{2\pi} \left[ \frac{\nu_g a_{th}}{q V_p \eta_{inj}} \right]^{1/2} = \frac{f_R}{(I_{pump} - I_{th})^{1/2}}$$

(4.2)

Where $\nu_g$ is group velocity, $a_{th} = \left. \frac{\delta g}{\delta N} \right|_{th}$ is differential gain at threshold, $V_p$ is mode volume, $q$ is electron charge and $\eta_{inj}$ is injection efficiency. The value of D-factor has been extracted by fitting above D-factor equation (Eqs. (4.2)) with the relaxation oscillation frequency ($f_R$) plot shown in Fig. 4.4. Extracted value of the figure of merit (D-factor) of the device is around 0.52 GHz mA$^{-1/2}$. The value of MCEF and D-factor shows good potentiality for direct modulation. The bandwidth and resonant frequency increases in proportion to the square root of the current above threshold as expected from the conventional rate equation analysis. The 3 dB bandwidth of a damping-free, parasitic-free semiconductor laser under direct current modulation can be expressed as

$$f_{3dB} = 1.55 f_R.$$

(4.3)

The damping and parasitic capacitance render the bandwidth ($f_{3dB}$) always smaller than 1.55 $f_R$ [20], which is normal phenomena and can be observed from Fig. 4.2. The relation becomes highly sub-linear when the pump current is increased further. In general to increase the 3 dB bandwidth of semiconductor laser diodes small signal modulation response ($S_{21}$), larger D-factor is desirable. As discussed in chapter two, one of the way to
enhance the D-factor is to reduce the current aperture size and increase the strain in quantum well [21], which is essential but not sufficient. In addition to that, short cavity, low parasitic impedance, impedance matching, better electron confinement, wavelength detuning, enhanced active area for nonlinear properties and higher photon density is also needed. So further investigation has been done to identify the scope of enhancement and contemporary limiting mechanism. The overall frequency response of a semiconductor laser to small-signal injection current modulation is the superposition of two independent responses namely the parasitic response and the intrinsic response [22]. The parasitic response is determined by extrinsic impedances that tend to distort the high frequency pulse shape and shunt current around the laser diode’s active layer. The intrinsic response is determined by the basic device physics governing operation of the laser and sets an upper limit on laser modulation speed [23]. Subsequently in an attempt to determine which mechanism causes modulation bandwidth to saturate with further pump current, the resonant frequency ($f_R$), parasitic roll-off frequency ($f_p$) and damping rate ($\gamma$) were extracted at several different values of pump current by fitting the three pole modulation transfer function approximation to the measured modulation response as shown in Fig. 4.2. Three pole modulation transfer function of active MMI-LD can be expressed as Eqs.(4.4) [24], [25].

\[
M(f) = \frac{f_R^2}{f_R^2 - f^2 + j\gamma(f/2\pi)} \cdot \frac{1}{1 + j(f/f_p)}
\] (4.4)
The three pole transfer function has been plotted and fitting has been done for several pump current values for accuracy and extracted damping rates and corresponding resonance frequencies are listed in Tab. 4.1.

Damping rate ($\gamma$) is proportional to the square of the resonance frequency and can be expressed as[26]

$$\gamma = K f_R^2 + \gamma_0$$

(4.5)

Where $\gamma_0$ is damping coefficient offset and K is intrinsic bandwidth determining factor. So the damping rate, which had been extracted from small signal modulation response ($S_{21}$) were plotted against the square of the resonance frequency. The resulting plot is presented in Fig. 4.5. Subsequently, the damping coefficient offset ($\gamma_0$) has been extracted from the crossing of the linear fit and vertical axis. The damping is proportional to the photon density but the resonance frequency only proportional to square root of photon density[27], leads to

Tab. 4.1 Damping rate and resonance frequency for several pump current.

<table>
<thead>
<tr>
<th>Pump current $I_p$ (mA)</th>
<th>Resonance frequency $f_R$ (GHz)</th>
<th>Damping rate $\gamma$ (ns$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>1.85</td>
<td>5.30</td>
</tr>
<tr>
<td>90</td>
<td>2.78</td>
<td>5.80</td>
</tr>
<tr>
<td>100</td>
<td>3.10</td>
<td>7.10</td>
</tr>
<tr>
<td>110</td>
<td>3.44</td>
<td>7.85</td>
</tr>
<tr>
<td>120</td>
<td>3.97</td>
<td>9.50</td>
</tr>
<tr>
<td>130</td>
<td>4.20</td>
<td>10.0</td>
</tr>
</tbody>
</table>
an intrinsic limitation of the modulation bandwidth due to strong damping in semiconductor laser diode, which is commonly described by the K-factor [2]. In general, the maximum possible intrinsic modulation bandwidth is determined solely by the K-factor [28]. The relation between extracted dumping rate and resonance frequency yields a K-factor of 0.352 ns and the dumping coefficient offset ($\gamma_0$) of 3.7 ns$^{-1}$. These value corresponds to an intrinsic bandwidth limit of 24.6 GHz. To best of our knowledge this is the highest intrinsic bandwidth reported for any active MMI-LD till date. The linear dependence of $f_{3dB}$ over the entire range of data suggests that the device is not limited by damping. Whereas the maximum extracted parasitic bandwidth limit from the experimental small signal modulation response ($S_{21}$) was ($f_{3dB,Parasitic} = f_{p,max}$) 6.5 GHz. Which demonstrates that the parasitic effect represent the major limitation to the device bandwidth. The analysis clearly
indicates the improvement of the parasitic reactance will result a very high 3 dB modulation bandwidth.

### 4.3 Bandwidth Dependency on Photon Density of Active Multimode Interferometer Laser Diode

As we discussed earlier in chapter three, designed active MMI-LD has a large MMI pump section behind the modulation section, which is able to generate a high photon density in the comparatively narrow width modulation section [29]. In general the laser modulation bandwidth is directly related the photon density [30]. So the reduction of the parasitic components indicates high modulation bandwidth for active MMI-LD and the potential of

![Graph showing intrinsic bandwidth as a function of photon density](image)

Fig. 4.6. Intrinsic bandwidth as a function of photon density showing required photon density in the modulation section for upto 40 Gbps operation.
this device in high speed low cost optical communication systems. Fig. 4.6 shows the experimental value of photon density and the calculation of the required photon density in modulation section generated from the pump section. By increasing the area size of the pump area in the next improved design, the photon density in the modulation section can be increased to the predicted level. The required photon density for the 24.6 GHz is approximately equal to $1.68 \times 10^{20} \text{ m}^{-3}$. So to achieve over 40 GHz, that may realize more than 40 Gbps modulation, it is obvious that more than $2.73 \times 10^{20} \text{ m}^{-3}$ photon density is required. Which is 60% higher than the present photon density but below the catastrophic facet damage level of InGaAsP. As the threshold for catastrophic facet damage in InGaAsP is at two orders of magnitude higher than for GaAs lasers [31], consequently the enhancement of photon density could lead toward a large bandwidth. So the higher photon density can be easily obtained by the enhancement of active area in MMI pump region. The required area size of the MMI pump section is approximately double than the current design. In this design, we used overly large-contact electrode pads for modulation which contributed a good amount of parasitic elements. Enhancement of modulation bandwidth is achievable with improved and low capacitance modulation section design, high photon density in the modulation section, enhanced and short active area and adoption of low parasitic package for LD chip.

4.4 Conclusions

With the split pump scheme for the active MMI-LD, High speed directly modulated asymmetric active MMI-LD were shown with 24.6 GHz of intrinsic 3 dB modulation
bandwidth. To the best of our knowledge, this is highest recorded intrinsic modulation bandwidth for active MMI-LD. The high speed modulation is limited by the cut-off frequency of parasitic RC (6.5 GHz), which can be improved by reducing the parasitic components. Even higher modulation speed is achievable by further increasing the photon density in the modulation section. The strategy to enhance the modulation bandwidth of the asymmetric active MMI-LD has been presented for above 40 GHz operation and the extracted value of photon density required to achieve 40 GHz, 3 dB bandwidth is $2.73 \times 10^{20}$ m$^{-3}$. Which can be easily achieved by enhancing the active area and size of the pump section together.

4.5 References


Chapter 5 Photon-photon Resonance in Active Multimode Interferometer Laser Diode

5.1 Introductory Overview

As discussed in chapter two, conventional laser bandwidth is limited by its material properties, photon density, photon lifetime, differential gain. So far discussion about the bandwidth enhancement had been limited mainly to higher photon density, higher current, making devices smaller to have a reduced volume, decreasing the photon lifetime by anti-reflecting coating and by having a higher differential gain. But still a significant enhancement in the modulation bandwidth is desirable and substantial efforts have been undertaken to increase the direct modulation bandwidth of laser through various methods. As discussed in chapter one, some of the proposed and demonstrated strategy for the enhancement of dynamic frequency response has involved the use of injection locking [1], photon-photon resonance (PPR) [2], push-pull modulation [3],[4], multiline interface [5], short cavity scheme [6],[7], tunnel injection[8] and modulator integration. Since the resonance frequency increases as the square root of the drive current above the threshold, high current densities may be required to increase the resonance frequency, which causes problems for long-term reliability. To overcome the intrinsic limitations of the laser diode, one of the promising approach along with the previously mentioned optimization is exploiting higher order resonances such as the photon-photon resonance (PPR) [9]–[13]. In case of active MMI-LD newly proposed and demonstrated hybrid approach is to push the carrier photon resonance (CPR) frequency by boosting up the photon density in modulation section [14],[15] up to the reliable level and enhance it further by inducing resonance between two spectrally neighbored longitudinal modes of the laser cavity [2], [16], [17], [12], generally known
as photon photon-photon resonance (PPR). Presence of the enhanced secondary resonance frequency in the modulation response, introduced by PPR results a significantly enhanced 3dB bandwidth. The existence of PPR has been demonstrated in DBR laser [2], [13], [16], passive feedback DFB (PF-DFB) laser [18], laterally-corrugated ridge-waveguide (LC-RWG) DFB [19], Optically controlled Passive feedback laser (OC-PFL)[20], coupled cavity injection grating (CCIG) laser [10], [21], vertical cavity surface emitting laser (VCSEL) [22],[23], quantum dot laser[21],[24] and laterally coupled diode lasers (LCDL)[25],[9]. The existence of PPR for DFB has also been simulated by mathematical model considering several longitudinal modes [26],[27][28]. In this chapter we have shown the possibility of extended modulation bandwidth by PPR in active MMI-LD. The prototype device concept and the experimental results shows the successful PPR by the MMI device structure. we have been able to successfully confirm a significantly enhanced resonance frequency of 11 GHz with direct modulation bandwidth of 15.2 GHz, due to enhanced photon density and advantage of having multimode section to explore PPR in active MMI-LD. Aforesaid enhancement is almost double then the last reported direct modulation bandwidth of 8 GHz [29]. Experimental success suggests that the PPR can be extended further by adjusting the device structure to increase mode spacing. This new mechanism for bandwidth enhancement should allow us to enhance the resonance frequency and far exceed the conventional direct modulation bandwidth of active MMI-LD.

5.2 Principle of Photon-photon Resonance

Semiconductor laser’s carrier photon resonance (CPR) is limited by the relaxation time of the excited electrons[18], [30]. However In active MMI laser cavity,
higher order modes are present. If these higher order modes can be utilized, the modulation speed could be strongly enhanced well beyond the relaxation frequency. To achieve PPR extended modulation bandwidth the device should allow multiple mode to interact with one another [2]. PPR becomes visible in the modulation response and significantly enhance the bandwidth, when it appears strong enough and at a moderate frequency distance from the carrier photon resonance (CPR) frequency at high bias current[2]. Simultaneously, distance between two resonances should be optimum to achieve flat response between them [11], otherwise bandwidth extension is not possible as shown in Fig. 5.1(black solid line). Following figure also shows that, the bandwidth extension is only possible when dip between the two resonances is filled up by their combined contribution (dotted red line). To stabilize the second resonance frequency as a function of bias current the thermal effect must be considered during design process [2]. Moreover keeping the device structure simple and easy to fabricate for the

![Diagram](image-url)

**Fig. 5.1.** Bandwidth extension as a result of photon-photon resonance
incorporation of photon-photon resonance is also an issue[9]. In this regard active multimode interference (MMI) is one of the most promising broad area structures. Active MMI-laser diode (active MMI-LD) offers regular single mode output [31], smaller size, simplicity of fabrication, high fabrication tolerance, low series resistance and compact split modulation section. In case of a conventional laser, as pump current is increased, both damping and CPR frequency increase with small change in photon density thereby limiting the maximum 3dB bandwidth. In active MMI-LD, as the tiny modulation section is separated in a narrow output port area and followed by a wide MMI active pump section. So the photon density is increased considerably with the increase of pump current, thereby allowing very efficient CPR modulation response up to 6 GHz measurement window[29], which is a desired characteristics for achieving flat response between CPR and PPR response. Furthermore, the use of separate contacts enables a supplementary flexibility in achieving the operation condition needed for obtaining PPR. Moreover, the designed MMI consists of asymmetric 1 X 1 multimode interferometer with both port connected to wave guide. The multimode structure allows multiple mode inside the laser cavity, which is a necessary condition for exploitation of PPR. Utilizing the above mentioned advantage, further enhancement of modulation frequency is achieved by introducing a second resonance peak in modulation response[32], occasioned by the interaction of spectrally neighbored longitudinal mode inside the multimode section of MMI-LD cavity.

5.3 Modulation Bandwidth Enhancement of Active MMI LD

A necessary prerequisite for the PPR is the existence of a weak additional mode used as a catalyst. Usually, the second mode has to be placed on the longer wavelength
side of the main mode in a distance equal to the desired position of the PPR [11], [21].

To excite a PPR peak at around 11 GHz, the distance of the main mode and the second mode has also to be 11 GHz, corresponding to a wavelength difference of ~ 0.08 nm.

Figure Fig. 5.2 (a) shows, the spectrum of the device emitting at a wavelength of 1561.95 nm with a side mode suppression ratio (SMSR) of about 35 dB and the inset picture shows magnified peak of emission. Inset picture in Fig. 5.2 (b) also shows the wavelength difference of the phase locked mode, which is around 0.08 nm. However, in order for the second resonance to be visible in the modulation response and to significantly enhance the bandwidth, it has to be strong enough and at a moderate frequency distance from the normal modulation resonance related to the carrier-photon interaction. In other words, the first resonance peak should occur at rather high frequencies, and reasonably good balance of power between main and side mode should be available[19]. As can be seen from the Fig. 5.2 (b), the gain of the second mode is

![Fig. 5.2. (a) Emission spectrum of active MMI-LD. (b) Inset picture shows the magnified peak of the emission.](image-url)
close to the main mode giving us advantage of having strong PPR effect. As we designed the MMI-LD’s modulation section volume to an extremely small value (150 µm²), so the device was expected to perform well under high frequency. The active MMI-LD has around 9.59 mW output power at 150 mA of pump current (I_{pump}) and 5 mA of modulation current (I_m). During measurement, high-speed probe is connected to the modulation section. The small signal modulation characteristics (S_{21}) of the active MMI-LD were evaluated under CW bias condition with a 65 GHz vector network analyzer (VNA), a bias-T, and a 65 GHz flat response photodiode. The measurement were repeated for various pump current (I_{pump}). The measured response was calibrated for the losses due to cables connectors and bias network using 12 term error correcting technique. Laser emission was focused by an anti-reflection (AR) coated lensed fibre and an optical isolator between the lensed fibre and detector has been employed to

![Fig. 5.3. Measured small signal modulation response (S_{21}) of active MMI-LD at different pump currents. Black oval circles are showing the position of the resonance peaks.](image)
reduce the reflection back to the laser and eliminate the small ripples in the modulation response that sometimes occur due to optical feedback. The dc current level was provided by the internal bias-T, while the modulation frequency was swept up to 16 GHz at an intervals of 19.9 MHz steps with constant optical power. The measured modulation response of the laser beam is presented as a function of the modulation frequency and the pump current in Fig. 5.3. The measured modulation bandwidth ($f_{3dB}$) was recorded 15.2 GHz at pump current fixed at 170 mA. Threshold current of the pump section was 65 mA when the modulation current was 5 mA. Threshold current density ($J_{th}$) was 4.45 KA/cm² for the pump section and the modulation current density was 2 KA/cm². Fig. 5.3 also shows the experimental data of small signal response of an asymmetric active MMI-LD with photon-photon resonance. A second strong resonance peaks can be seen in the figure due to multiple mode phase locked condition. For having PPR peak the phase locking must be stable over time. So the existence of PPR peak verifies the

![Graph](image-url)

Fig. 5.4. Bandwidth saturation contributed by CPR only.
constant phase difference for long time[33]. Thanks to the MMI section, which enables the single mode optical field at the input to be identically imaged at the MMI output and paved the way for easier phase lock condition[34],[35]. Concerning the CPR peak, we observe the same behavior as in conventional lasers. With increasing bias current, the resonance frequency shifts to higher frequencies and become saturated at around 120 mA ($I_{\text{pump}}$) of pump current as shown in Fig. 5.4. Simultaneously, the second resonance becomes stronger with further pump current increment leading to an immense increase of the modulation bandwidth above 160 mA of pump current, as shown in Fig. 5.5. This is very important in practical applications because the gap between the traditional CPR and the PPR in the small signal intensity modulation (IM) response should be flattened by the contribution of the two effects in order to avoid unwanted dip in the device modulation response (Fig. 5.3). For this reason the CPR response should be as wide as possible and the PPR amplitude should be strong enough for higher injection current to

![Graph](image.png)

Fig. 5.5. Measured 3 dB bandwidth as a function of the square root of the pump current above threshold.
have flat response between them. Fig. 5.3 shows a similar situation for a pump above 160 mA. The first resonance caused by interplay of carriers with the photon field stays fixed at about 6 GHz. The second resonance peak at 11 GHz is due to cavity interference effects caused by the interaction of multiple modes inside the multimode section of the laser. Without the presence of the second resonance, the 3 dB modulation bandwidth would be 8 GHz estimated by fitting the standard transfer function model to the CPR peak. At a pump current of 170 mA, large enhancement in modulation bandwidth of over 15.2 GHz can be experimentally obtained, that corresponds to more than 12.6 GHz improvement compared to 2.6 GHz previously reported for active MMI-LD[36]. The frequency relaxation oscillation ($f_R$) versus the square root of the current above threshold ($I_{\text{pump}} - I_{\text{th}})^{1/2}$ has been presented in Fig. 5.5. The bandwidth increased up to 8 GHz in proportion to the square root of the current above threshold as expected from CPR

![Graph showing PPR peak amplitude with increasing pump current and dependency of PPR on pump current.](image)

Fig. 5.6. PPR peak amplitude with increasing pump current and dependency of PPR on pump current.
induced bandwidth calculation. Fig. 5.5 also shows the 15.2 GHz enhanced bandwidth due to flat response between CPR and PPR at 170mA of pump current. The value of the modulation current enhancement factor (MCEF) has also been extracted, which corresponds to a value of 1.38 GHz mA⁻¹/². The value shows good potentiality for direct modulation. The amplitude of the second resonance can be tuned, depending on the injected pump current, from a relatively strong peak to a relatively flat response (Fig. 5.6). With increasing pump current flat response between CPR and PPR can be achieved. Change of the amplitude of second resonance (PPR) influenced by the pump current is presented in Fig. 5.6. The dotted trend line fitted to the experimental data shows the linear increasing trend of the PPR peak with increasing pump current. This may cause due to the contribution of the increasing coupling of the phase locked weak mode with increasing pump current. Fig. 5.6 also shows the frequency shift of the PPR peak with increasing pump current. In addition to the PPR amplitude, PPR peak shift as a function

![Graph](image)

**Fig. 5.7.** Intrinsic bandwidth as a function of photon density showing the required photon density in the modulation section for 40 GHz CPR induced bandwidth.
of the pump current ($I_{pump}$) has also been presented in Fig. 5.6. From this figure it is evident that the PPR frequency is not much affected by any variation of pump current. That particular behavior is expected for photon-photon resonance peak, if the phase tuning section is not present in laser[25] and experimentally verified. Figure 6 shows the experimental value of photon density and the calculation of the required photon density in modulation section, originated from the pump section. The required photon density of $2.73 \times 10^{20} \text{m}^{-3}$ for the 40 GHz CPR induced 3dB bandwidth has also been extracted from Fig. 5.7. Present pump section area size (1460 $\mu \text{m}^{2}$) can be enhanced and increased to 2336 $\mu \text{m}^{2}$ in the next improved design, to achieve the required photon density [37]. The relation between the mode separation and PPR frequency is presented as mode separation function in Fig. 5.8. As a linear prediction from the current experimental PPR position, we are expecting around 73 GHz PPR positioning is needed to achieve around 100 GHz of PPR induced extended 3dB bandwidth. The above mentioned PPR positioning corresponds to a 0.6 nm of mode separation and may be

![Mode Separation vs. Frequency Graph](image)

**Fig. 5.8.** PPR frequency as a function of mode separation showing required mode separation corresponding 40-100GHz of PPR peak positioning.
achievable by proper adjustment of the device port lengths and simultaneously introducing a phase tuning section[38] near the rear facet of the active MMI-LD.

5.4 Conclusion

Enhanced resonance frequency of 11 GHz and 3dB bandwidth of more than 15.2 GHz has been experimentally verified for active MMI-LD. As this research is ongoing, the fundamental limit has not yet been reached. The Modulation response shows a second resonance peak above the relaxation oscillation frequency with a value that corresponds the mode separation. The required design issues has also been predicted for the realization of 100 GHz extended bandwidth. The demand for the 100GHz bandwidth for the short distance communication is high and to meet the demand, simultaneously enhancement of the carrier photon resonance along with higher photon-photon resonance may open up the road towards highly desired 100 GHz of extended direct modulation bandwidth for active MMI-LD.

5.5 References


Chapter 6  Conclusions and Future Work

6.1  Conclusions

Laser diode capable of high speed direct modulation is one of the key solution for short distance applications due to their low power consumption, low cost and small size features. So realization of high modulation bandwidth for direct modulated laser maintaining the above mentioned feature is needed to enhance the short distance low cost data transmission. Continuously growing market demand for high bandwidth direct modulation laser is the motivation behind the research. So to achieve this target 1.55-μm InGaAsP/InGaAsP Multiple quantum well (MQW) asymmetric active Multi Mode Interferometer Laser diode (active MMI-LD) has been demonstrated. In this dissertation, we have presented principle of the active MMI-LD for the incorporation of photon-photon and for the first time and successfully demonstrated the occurrence of photon-photon resonance in the fabricated prototype active MMI-LD for bandwidth enhancement. The successful presence of PPR opens up the possibility of ultra-high direct modulation bandwidth active MMI-LD that emit at a wavelength of 1.55 μm. We also demonstrated the carrier photon resonance related intrinsic modulation bandwidth of active MMI-LD is as high as 26.4 GHz with a possibility to enhance it up to 40 GHz that eventually can team up with the PPR induced bandwidth enhancement towards the achievement of 100 GHz 3 dB bandwidth. The design criteria for 100 GHz 3dB bandwidth is also calculated from the existing experimental data and presented in this dissertation. We also investigated the large
signal modulation performance of active MMI-LDs. Key achievements of this research has been summarized in the later sections as follows:

(1) Split pump concept for active MMI-LD with enhanced frequency response is presented. More than 5.8 GHz resonance frequency with 8 GHz 3 dB bandwidth and clear eye diagram at 2.5 Gbps for a 2^7-1 pseudorandom binary sequence had been demonstrated indicating the potentiality of this laser as directly modulated light source [1]–[3].

(2) With the split pump scheme for the active MMI-LD, High speed directly modulated asymmetric active MMI-LD were shown with 24.6 GHz of intrinsic 3 dB modulation bandwidth. To the best of our knowledge, this is highest recorded intrinsic modulation bandwidth for active MMI-LD. The high speed modulation is limited by the cut-off frequency of parasitic RC (6.5 GHz), which can be improved by reducing the parasitic components. Even higher modulation speed is achievable by further increasing the photon density in the modulation section. The strategy to enhance the modulation bandwidth of the asymmetric active MMI-LD has been presented for above 40 GHz operation [4]–[6].

(3) Enhanced resonance frequency of 11 GHz and 3dB bandwidth of more than 15.2 GHz has been experimentally verified for active MMI-LD. The Modulation response shows a second resonance peak above the relaxation oscillation frequency with a value that corresponds the mode separation. The extracted value of photon density required to achieve 40 GHz, 3 dB bandwidth is $2.73 \times 10^{20} \text{ m}^{-3}$. Which can be easily achieved by enhancing the active area and size of the pump section together. The required design issues has also been predicted for the realization of 100 GHz extended bandwidth [7]–[11].
6.2 Future Work

As this research is ongoing, the fundamental limit has not yet been reached. So far the research work presented in this dissertation has yielded highest reported intrinsic modulation bandwidth for active MMI-LD and first observation of photon-photon resonance in a grating-less easy to fabricate device structure. But there are always further improvements that could be done to enhance the performance. The main restriction of the high output power has been confirmed to be the parasitic limitation of the device. Therefore, to optimize the direct modulation bandwidth, the further process development can be focused on the device structure aspect, which if improved, can directly lead to lower parasitic impedances and ultimately better modulation performance. Another aspects needed to be considered is the enhancement of photon density by enhancing the active area and increasing the size of the pump section of the laser diode along with proper mode separaton to optimize and enable a flat response between the resonance peaks.

The demand for the 100GHz bandwidth for the short distance communication is high and to meet the demand, simultaneous enhancement of the carrier photon resonance along with higher photon-photon resonance may open up the road towards highly desired 100 GHz of extended direct modulation bandwidth for active MMI-LD.

6.3 References


Appendix A: Principles of Multimode Interferometer

Basic principles of MMI theory has been explained by L. B. Soldano and E.C.M. Pennings [1]. Most of the MMI devices were passive but based on the MMI theory first novel active light emitting device (active MMI-LD) has been invented and demonstrated by K. Hamamoto [2],[3]. In the Appendix A, we make a summary about the basic principles of MMI theory. Most of the high performance MMI device consist of two parts, one of them is access waveguide and the other one is multimode waveguide [4]. Number of access waveguide and width of them depends on the design of the device. Usually the access waveguides are mostly designed as single mode waveguide. The central structure of an MMI device is a multi-mode waveguide designed to support a large number of modes (typically ≥ 3). In a step-index multimode waveguide of width $W_{MMI}$, High mesa (effective) refractive index $n_r$ and cladding (effective) refractive index $n_c$, the waveguide supports $m$ lateral modes with mode numbers $\nu = 0, 1 \ldots (m-1)$ at a free-space wavelength $\lambda_0$. The propagation

![Fig. A.1. NxM Multimode Interference Coupler](image-url)
constant is noted \( \beta_0 \). We note the “effective” width \( W_{ev} \), takes into account the (polarization-dependent) lateral penetration depth of each mode field, associated with the Goos-Hänchen shifts at the high mesa boundaries. For high-contrast waveguides, the penetration depth is very small so that \( W_{ev} \approx W_{MMI} \). In general, the effective widths \( W_{ev} \), can be approximated as

\[
W_{ev} = W_{MMI} + \left( \frac{\lambda_0}{\pi} \right) \left( \frac{n_c}{n_r} \right)^2 \sigma (n_r^2 - n_c^2)^{-1/2}
\]  

(A.1)

Propagation constant difference of two lowest order modes can be represented in terms beat length \( L_{\pi} \) as

\[
L_{\pi} = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4n_l W_{ev}^2}{3\lambda_0}
\]  

(A.2)

The propagation constants difference of mode \( (\nu) \) and fundamental mode (propagation constant spacing) can also be expressed as:

\[
(\beta_0 - \beta_{\nu}) \approx \frac{\nu(\nu + 2)}{3L_{\pi}} \pi
\]  

(A.3)

where \( \nu \) is the mode number. An input field profile \( E(x, 0) \) imposed at \( z = 0 \) and restricted within the multimode waveguide, contains multiple mode and can be expressed as summation of mode dependent modal field distributions as
\[ E(x,0) = \sum_v c_v E_v(x) \quad (A.4) \]

where the summation includes the radiative modes along with guided modes. The field excitation coefficients \( c_v \), can be estimated using overlap integrals based on the field-orthogonality relations.

\[ c_v = \frac{\int E(x,0)E_v(x)dx}{\sqrt{\int E_v^2(x)dx}} \quad (A.5) \]

If the input field \( E(x,0) \) does not excite radiative modes it can be decomposed in terms of the \( m \) guided modes only and the initial input field can be written as

\[ E(x,0) = \sum_{v=0}^{m-1} c_v E_v(x) \quad (A.6) \]

The field profile at a distance “\( z \)” along Z axis can be written as a superposition of all the guided mode field distributions as

\[ E(x,z) = \sum_{v=0}^{m-1} C_v E_v(x) \exp[j(\omega t - \beta_v z)] \quad (A.7) \]

A useful expression for the field at a distance \( z = L \) is then found by substituting Eqs. (A.3) into Eqs. (A.8)

\[ E(x,L) = \sum_{v=0}^{m-1} C_v E_v(x) \exp[j\frac{\nu(v+2)\pi}{3L_\nu} L] \quad (A.8) \]

Under certain circumstances, the field \( E(x,L) \) can create an identical image of itself (self-imaging) independent of modal excitation. The phenomenon is expressed below in brief.
\[ \nu(\nu + 2) = \begin{cases} \text{even for } \nu \text{ even} \\ \text{odd for } \nu \text{ odd} \end{cases} \quad (A.9) \]

\[ E_\nu(-x) = \begin{cases} E_\nu(x) \text{ for } \nu \text{ even} \\ -E_\nu(x) \text{ for } \nu \text{ odd} \end{cases} \quad (A.10) \]

Eq. (A.8) shows that \( E(x, L) \) will be a self-image of \( E(x, 0) \) if the mode phase factor satisfies the following condition

\[ \exp\left[j \frac{\nu(\nu + 2)\pi}{3L_\pi} L\right] = 1 \text{ or } (-1)^\nu \quad (A.11) \]

According to above conditions for self-image, the phase changes of all the modes along \( L \) must differ by integer multiples of \( 2\pi \). In this case, all guided modes interfere with the same relative phases as in \( z = 0 \) (Input field positon). The image is thus a direct replica of the input field. Also the phase changes must be alternatively even and odd multiples of \( \pi \). In this case, the even modes will be in phase and the odd modes in antiphase. Because of the odd symmetry stated in Eqs. (A.9) and Eqs. (A.10), the interference produces an image

Fig. A.2. Schematic of a multi-mode waveguide about the formation of self-images. A mirrored single image at \( (3L_\pi) \), a direct single image at \( 2(3L_\pi) \), and two-fold images at \( 1/2(3L_\pi) \) and \( 3/2(3L_\pi) \).
mirrored with respect to the plane $x = 0$. Taking into account Eqs. (A.9) and Eqs. (A.10), it is evident that the first and second condition of Eqs. (A.11) will be fulfilled at $L = p (3L_{\pi})$ with $p = 0, 1, 2 \ldots$ for $p$ even and $p$ odd, respectively. In addition to the single images at distances given above, multiple images can be found as well. Let us consider the images obtained half-way between the direct and mirrored image positions, i.e., at distances $L = p/2(3L_{\pi})$ with $p = 1, 3, 5\ldots$The filed distribution at this length $L = p/2(3L_{\pi})$ can be expressed as

$$E(x, \frac{p}{2}3L_{\pi}) = \frac{1+(-j)^p}{2} E(x, 0) + \frac{1-(-j)^p}{2} E(-x, 0) \quad (A.12)$$

Eqs. (A.12) shows that both the direct and mirrored images of the input field $E(x,0)$ occur simultaneously, each with an amplitude of $1/\sqrt{2}$ and with a phase difference of $\pi/2$, at distances $z = 1/2(3L_{\pi}), z = 3/2(3L_{\pi}),\ldots$, as shown in Fig. A.1. This type of two-fold imaging is often used as a 3-dB MMI coupler.

References


Appendix B: Conventional High Speed LDs

Recent years have seen considerable progress in the area of semiconductor lasers. State of the art silica fibers have minimum dispersion at 1.3 µm and transmission loss (0.2 dB/km) at 1.55 µm wavelength. Semiconductor emitters operating at these wavelengths are therefore very important [1]. A bunch of different structured lasers containing InGaAsP and AlGaInAs active layer have been successfully developed for these wavelengths. Single longitudinal mode lasers operating at 1550 nm is necessary in minimizing the effects of higher dispersion in standard single mode fiber. A number of approaches have been developed to achieve single mode operation, but the basic principle is to provide a filter mechanism, either inside laser cavity or external to select a particular operating wavelength [2].

B.1 Distributed Feedback Laser

Distributed feedback (DFB) laser has become the predominant single mode laser used in PON and DWDM communication systems. To achieve single wavelength lasing diffraction gratings are needed close to the p-n junction of the diode. This grating acts like an optical filter. Optical wave travelling across the active region is partially reflected at the peaks and valleys of the grating because of the difference in the effective refractive index. Only that wavelength for which this feedback interferes constructively (Bragg wavelength) is amplified and the rest are suppressed [3]. At least one facet of a DFB is anti-reflection coated. Schematic diagram of a conventional DFB laser is shown in Fig. B.1. The DFB laser’s emission wavelength can be set during manufacturing by the pitch of the grating and
the grating makes the emission wavelength fairly independent of temperature. Spectral characteristics of DFB lasers shows reduction in the spectral width and nearly total suppression of side bands. DFB lasers are widely used in long distance optical communication where a precise and stable wavelength is critical. In comparison to an FP wafer, the fabrication of a DFB wafer is more complex requiring additional steps.

![DFB laser diagram](image)

Fig. B.1. Schematic of a DFB laser

Directly modulated DFB lasers can achieve record high bit rates of 56 Gbps over moderate and long distances at low dispersion (1310 nm) transmission window [4] and more than 40 Gbps at 1550 nm low loss transmission window [5].

### B.2 Distributed Bragg Reflector Laser

A distributed Bragg reflector laser (DBR) is a type of single frequency laser diode which can be formed by replacing one or both of the discrete laser mirrors with a passive grating reflector. Fig. B.2 shows a schematic of such a laser with rear grating mirror. DBR laser’s optical cavity consist of an electrically or optically pumped gain region. At least one of the mirror is wavelength selective in DBR laser due to the Bragg grating, resulting in lasing at a single resonant frequency. The front mirror is usually coated with anti-reflection (AR) coating to allow light emission. The passive grating reflector is a wavelength selective structure that consists of periodically structured diffraction grating. Since the refractive
index of the Bragg section depends on the carrier density this can be exploited to vary the refractive index electro optically on the sections by incorporating a separate electrode pad.

![Fig. B.2. Schematic of a DBR laser](image)

Widely tunable lasers covering the entire C [6][7] or L-band [7] have been developed and commercially available from multiple vendors. DBR laser emitting at 1.55µm with 40 Gbps modulation characteristics had also been reported [8].

**B.3 Distributed Reflector Laser**

![Fig. B.3. Schematic of a DR laser](image)

The DR laser consists of active region, sandwiched between front passive reflector and rear passive reflector. The grating is present in both active and passive reflector regions. The reflectors can reduce the threshold gain of the DR laser by increasing feedback to the active region. DR laser’s directly modulation character is superior. Recently, high-speed direct modulation of 1.55-µm DR laser is reported up to 40-Gb/s at 85°C [9].
B.4 Vertical Cavity Surface Emitting Laser

The emission direction in a vertical cavity surface emitting laser (VCSEL) is perpendicular to the wafer surface and along the direction of current flow. This vertical feature makes it possible to achieve very short cavity. Cross sectional view of a conventional VCSEL is illustrated in Fig. B.4. The cross sectional view shows that the active region is sandwiched between two high reflectivity DBR mirrors. As the active gain region is short in length, mirrors with high mean reflectivity (usually > 99 %) are required to achieve lasing condition. The high reflection is achieved by using dielectric mirrors made from alternating high and low refractive index quarter-wave thick multilayer. Such dielectric mirrors provide a high degree of wavelength-selective reflectance. The top of the device is metallized for contacting but a circular aperture is created for light emission. The device produces an emitted beam with a circular far field, which is beneficial when coupling light to an optical fiber. An advantage of VCSELs over edge emitter laser is that the vertical geometry facilitates wafer level testing of the devices. Recently, high-speed direct modulation of 1.55-\(\mu\)m VCSEL is reported up to 40-Gb/s with 19 GHz of 3dB Bandwidth [10].

Fig. B.4. Cross sectional view of a VCSEL
B.5 Fabry Pérot Lasers

The simplest semiconductor laser diode structure is the Fabry Pérot (FP) laser, where a resonator is formed by placing a gain medium between two mirrors. Mirrors are formed by cleaved facet. Uncoated cleaved facet can provide approximately 30% reflectivity. The amount of reflectivity can be changed by placing a high reflectivity (HR) coating on the back facet and an anti-reflectivity (AR) coating on the front facet. FP lasers have no mechanism for frequency selectivity and produce a multimode spectrum. The spectral modes are equally spaced in frequency. FP lasers are important source in optical communications especially for short reach low cost applications. Relative simplicity of the structure and non-necessity of optical isolator makes it cost effective to produce with high yields.

Directly modulated FP lasers can achieve relatively high bit rates over short distances at low dispersion (1310 nm) transmission window. 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 distance communication. Some recent report shows, Fabry-Perot (Quantum Dot) laser can provide an enhanced modulation bandwidth up to 11 GHz and 25 Gbps large signal direct modulation at 1.3 µm [11]. Another report shows an improved bandwidth of an injection-locked FP laser at around 10.5 GHz [12].

B.6 References


Appendix C: Scattering Parameters

An electrical network can be considered as a 'black box' containing various interconnected electrical components such as resistors, capacitors, inductors that interacts with other circuits through ports. S-parameter matrix can be used to calculate its frequency response when signal is applied to the ports. S-parameters was first described by Vitold Belevitch[1], [2] and later popularized by Kaneyuki Kurokawa[3]. Presently, S-parameter analysis is very important for laser diode characterization so this brief appendix is included in this thesis for basic understanding of the scattering parameters.

\[ S_{11} = \frac{V_{\text{reflected at port 1}}}{V_{\text{incident at port 1}}} \]  
\[ S_{21} = \frac{V_{\text{output at port 2}}}{V_{\text{incident at port 1}}} \]

Fig. C.1. S-Parameters of active MMI-LD
\[
S_{12} = \frac{V_{\text{output at port 1}}}{V_{\text{incident at port 2}}} \quad \text{(C.3)}
\]

\[
S_{22} = \frac{V_{\text{reflected at port 2}}}{V_{\text{incident at port 2}}} \quad \text{(C.4)}
\]

During the measurement of the scattering parameter of laser diode as device under test (DUT) \( S_{12} \) represents the power transferred from Port 2 to Port 1. \( S_{21} \) represents the power transferred from Port 1 to Port 2. \( S_{11} \) and \( S_{22} \) represents the power reflected back to respective ports. For the characterization of laser diode \( S_{21} \) and \( S_{11} \) are very important as they can explain the frequency response and the condition of impedance mismatch of the laser diode. It is even possible to indirectly measure the impedance of the laser diodes at very high frequency using scattering parameter and equivalent circuit model of laser diode.

References


Appendix D: Thin Film Coating

Optical thin film anti-reflection (AR) or high reflection (HR) coatings are used to alter the reflectance and transmittance properties of semiconductor lasers. The optics being coated is usually called the substrate. The advantage of magnetron sputtering includes metallic target material can be sputtered without decomposition and non-conductive materials can be sputtered by using radio frequency (RF) with excellent layer uniformity. Active MMI-LD has been coated with both HR and AR coating using magnetron sputtering technique. Coating materials is located inside the chamber on a magnetron in a solid form called target.

Fig. D.1. (a) Chamber of the sputtering machine. (b) Target material inside chamber. (c) Active MMI-LD inside the holder of the sputtering machine.
Magnetron sputtering technology uses magnetic fields to keep the plasma in front of the target, intensifying the bombardment of ions. The magnetron sputtering plasma coating is deposited in high vacuum using the process of evaporation by bombardment of ions to the target surface\[1\]. The chamber has been highly vacuumed due to removal of almost every molecule from the chamber. This type of clean environment with only coating materials has been ensured for highly pure contamination less coatings. The next step of the sputtering process has been done in a vacuumed chamber filled with Argon gas (to create inert gas environment). Ions are charged particles so magnetic fields has been used to control their velocity and behavior. Radio frequency (RF) magnetron source has been utilized for inducing high energy state during magnetron sputtering. By applying a high voltage a glow discharge plasma has been created to accelerate ions to the target active MMI-LD. The accelerated argon ions ejected sputtering materials, in our case amorphous silicon (a-Si) or Silicon dioxide (SiO$_2$), resulting alternating layer of thin films or a single layer thin film

![Graph](image-url)

**Fig. D.2.** Calculated energy reflectance (R) of single layer AR coating
deposition on laser facet. By controlling the deposition rate the film thickness can be controlled precisely to accumulate HR or AR coating [1]. The calculation for active MMI-LD has been performed to find out the required thickness and resulting reflectivity for that.

Fig. D.3. Calculated layer thickness of HR coating for active MMI-LD

Fig. D.4. Calculated energy reflectance (R) of three layer HR coating
particular pattern of layers with specific thickness. The thickness of 269 nm has been found optimum for AR coating to obtain around 5% reflectivity in front facet of the active MMI-LD as sown in Fig. D.2. For high reflection coating the alternative layer of amorphous silicon (a-Si) or Silicon dioxide (SiO₂) deposition is needed and the calculated thickness of the layers to achieve high reflectivity are presented in Fig. D.3. Resultant calculated reflectivity is presented in Fig. D.4 [2].

References


# List of Acronyms

The following table describes the significance of various abbreviations and acronyms used throughout the thesis. Nonstandard acronyms that are used in some places are not in this list.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AR</td>
<td>Anti-Reflection</td>
</tr>
<tr>
<td>Au</td>
<td>Aurum (Gold)</td>
</tr>
<tr>
<td>ADSL</td>
<td>Asymmetric Digital Subscriber Line</td>
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<tr>
<td>B</td>
<td></td>
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<td>B-PON</td>
<td>Broadband Passive Optical Network</td>
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<tr>
<td>BERT</td>
<td>Bit Error Rate Tester</td>
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<tr>
<td>BW</td>
<td>Bandwidth</td>
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<td>C</td>
<td></td>
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<tr>
<td>CWDM</td>
<td>Coarse Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>CATV</td>
<td>Cable Television</td>
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<tr>
<td>CPR</td>
<td>Carrier Photon Resonance</td>
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<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>D</td>
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<tr>
<td>DBR</td>
<td>Distributed Bragg Reflector</td>
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<tr>
<td>DFB</td>
<td>Distributed Feedback</td>
</tr>
<tr>
<td>DR</td>
<td>Distributed Reflector</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<td>Down Stream</td>
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<tr>
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<td>Dense Wavelength Division Multiplexing</td>
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<tr>
<td>DML</td>
<td>Directly Modulated Laser</td>
</tr>
<tr>
<td>E</td>
<td></td>
</tr>
<tr>
<td>EA</td>
<td>Electro Absorption</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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</tr>
<tr>
<td>ER</td>
<td>Extinction Ratio</td>
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<td>Externally Modulated Laser</td>
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<td>Electro-absorption modulator</td>
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<td>FEC</td>
<td>Forward Error Correction</td>
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<td>FSR</td>
<td>Free Spectral Range</td>
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<td>FTTH</td>
<td>Fiber To The Home</td>
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<td>FM</td>
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<td>Gallium Arsenide</td>
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<td>Ground Signal Ground</td>
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<td>Gbps</td>
<td>Giga bits per second</td>
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<td>Gigahertz</td>
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<td>Gigabit Passive Optical Network</td>
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<tr>
<td>HSPD</td>
<td>High Speed Photo Diode</td>
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<td>HR</td>
<td>High-reflection</td>
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<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>ICP</td>
<td>Inductively Coupled Plasma</td>
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<tr>
<td>InGaAsP</td>
<td>Indium Gallium Arsenide Phosphide</td>
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<td>IM</td>
<td>Intensity Modulation</td>
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<tr>
<td>KA</td>
<td>Kilo Ampere</td>
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<td>Modulation Current Efficiency factor</td>
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<td>Multi-Mode Interferometer</td>
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<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td>MQW</td>
<td>Multiple Quantum Well</td>
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<td>MAN</td>
<td>Metropolitan Area Network</td>
</tr>
<tr>
<td>N</td>
<td>Non Return to Zero</td>
</tr>
<tr>
<td>NRZ</td>
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<td>NG-PON2</td>
<td>Next Generation Passive Optical Network Stage 2</td>
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<tr>
<td>O</td>
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<tr>
<td>OEO</td>
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</tr>
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<tr>
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<tr>
<td>OSA</td>
<td>Optical Spectrum Analyzer</td>
</tr>
<tr>
<td>P</td>
<td>Pulse Pattern Generator</td>
</tr>
<tr>
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<tr>
<td>PRBS</td>
<td>Pseudo-Random Bit Sequences</td>
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<tr>
<td>SA</td>
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<td>SOA</td>
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<td>SAN</td>
<td>Storage Area Network</td>
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<td>Definition</td>
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<tr>
<td>SMSR</td>
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<tr>
<td>XG PON</td>
<td>10-Gigabit-capable passive optical network</td>
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# List of Symbols

<table>
<thead>
<tr>
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<tr>
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<td>$dg/dn$</td>
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<td>Number of Quantum Well</td>
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<td>Ohm</td>
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<td>W</td>
<td>Watt</td>
</tr>
<tr>
<td>$\mu$m</td>
<td>Micro Meter</td>
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<td>$J_{th}$</td>
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<td>Electron Volt</td>
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<td>nm</td>
<td>Nano Meter</td>
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<td>Decibel</td>
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<td>VPP</td>
<td>Voltage Peak to Peak</td>
</tr>
<tr>
<td>ns</td>
<td>Nano Second</td>
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</table>
$L_\pi$  
Beat Length

$c_v$  
Field Excitation Coefficients

$E(x, 0)$  
Input Field

$S_{21}$  
Small Signal Modulation Characteristics

K-factor  
Intrinsic Bandwidth Determining Factor

\[ a_{th} = \left. \frac{\delta g}{\delta N} \right|_{th} \]  
Differential Gain at Threshold

$V_p$  
Mode Volume

$\eta_{inj}$  
Injection Efficiency

$\gamma_0$  
Dumping Coefficient Offset

$n_c$  
Cladding (effective) Refractive Index

$n_r$  
High mesa (effective) Refractive Index
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I had a dream to carry on my research under direct supervision of the inventor of that particular field of study. My dream became true when my supervisor Professor Dr. Kiichi Hamamoto accepted me as one of his students. So first of all, I would like to thank my supervisor Professor for accepting me as one of his students to work on this very exciting field of research. I would also like to thank him for the kind guidance, advice, scientific freedom, research fund, industrial collaboration, conference fund for numerous local and international conferences, rich experimental setup and patience in correcting my manuscripts throughout the course of my research. I would also like to thank Prof. Dr. Kazutoshi Kato for his time to time kind assistance, laboratory support and discussion about my experimental setups. I would like to express my sincere thanks to Green platform research laboratories, NEC Corporation for their industrial collaboration and support. Special thank goes to the Principal researcher Mr. Akio Tajima for his valuable comments and discussion. I would also like to thank assistant professor Dr. Jiang Haisong for her numerous support. I must thank Prof. Hiroshi Nakashima, Prof. Kazutoshi Kato and Prof. Yoshiyasu Ueno for reviewing my thesis work and their valuable comments.

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