Development of Vertical Cavity Surface Emitting Laser Modulation for Data Communication

Yixin Cao

School of Telecommunication Engineering (STE), XIDIAN University, Xi’an, Shaanxi, 710126, China

ABSTRACT-This paper includes some basic knowledge of VCSEL and reviews some researches focusing on development of modulation characteristics in data communication of 850nm, 980nm, 1060nm and 1100nm VCSEL, which is helpful to researchers who are studying in this field. The popular modulation in data communication VCSEL is also mentioned in this paper. There are still some difficulties in the modulation of VCSEL-based links directly, which may be solved by modulating relaxation-oscillation frequency of VCSEL in the near future.

1. INTRODUCTION
Due to some limitations of Edge Emitting Laser (EEL), such as in-chip detection cannot be carried out by EEL and its output light spot is not circular symmetrical. Professor IGA of the University of Tokyo introduced the concept of Vertical Cavity Surface Emitting Laser (VCSEL) in 1997. Then in 1979 the IGA team invented the first VCSEL and then continued to develop it. The first RT, CW VCSEL was developed by IGA and Koyama. In 1990, scientists invented the VCSEL with different wavelength including 850nm, 1310nm, 1550nm. The blue ray VCSEL is mainly used for treatment and storage, infrared light is used to detect polluting gases. Based on various advantages of VCSEL, it is widely used now. Here, 850nm, 980nm, 1060nm and 1100nm VCSEL’s modulations are mainly introduced in this paper.

2. OVERVIEW OF VCSEL

2.1 Basic structure and working principle
There are some different structures of VCSEL. The typical VCSEL is composed of an oxide layer, an active layer with quantum well, a pair of electrodes and a pair of Distributed Bragg Reflectors (DBR) (see figure 1). A DBR consists of multiple layers of alternating materials with high refractive index and low refractive index, which is used to improve the reflective index and achieve a near-total reflection in a particular range of wavelength. The thickness of each layer of DBR is a quarter of the wavelength of the emitted light. The main advantage of the DBR over ordinary mirrors is that it can be designed to have a custom reflectivity at a selected wavelength. Oxide layer is designed to shape the light spot to make it circular symmetrical, which can help VCSEL improve its efficiency of coupling with the optical fiber and the gain. And multiple quantum wells (MQWs) in Active layer are look like wells that the electrons and holes are restricted in the potential well before they have time to neutralize with each other. MQWs result in a high injection efficiency and it is easy to realize the population inversion. Therefore, the gain of VCSEL will be greatly increased.
2.2 Application of VCSEL

Based on the structure of VCSEL, it has numerous applications in the daily life (see figure 2). 940nm VCSEL is applied in 3D sensing by Apple because of its High Power Conversion Efficiency (PCE), which is a quite popular application currently. In addition, VCSEL can be applied in Illumination, Processing, Display, LiDAR, Optic Communication (OC) and other fields. This paper mainly introduces properties of VCSEL in Data Communication in recent years.

2.3 Advantages of VCSEL

Compared with classic Edge Emitting Laser (EEL), VCSEL has a lot of advantages. Firstly, based on the structure of cavity, the divergence angle is small and output beam spot is circular symmetric, which makes it easier to be coupled with optical fibre. Secondly, because of its small size, VCSEL is proper to be integrated into a high-density two-dimensional array. Thirdly, the direction of the output beam is vertical to the surface, so it can be used in parallel optical interconnections and data communication. What is more, the short cavity and the mode selecting characteristics of DBR allows the VCSEL to be able to work in dynamic single longitudinal mode. Based on these advantages, VCSEL can be used in data communication.
3. ANALYSIS ON VCSEL

3.1 Modulation characteristic of VCSEL at RT

There are some ways to gain a higher modulation bandwidth. For instance, a small oxide aperture and a short cavity can give a high confinement factor. Modulating the DBR’s phase can gain a low photon lifetime. All these operations are helpful for increasing the modulation bandwidth. Table 1 shows some properties of VCSEL at room temperature, such as Modulation Bandwidths and Bit Rates and Oxide Aperture, which were invented by various groups.

| Group   | λ (nm) | Bandwidth (GHz) | Bit Rate (Gbps) | Temperature (°C) | Oxide Aperture (μm) | Year |
|---------|--------|-----------------|-----------------|------------------|---------------------|------|
| IBM     | 850    | 15.4            | 20              | 25               | 8                   | 2001 |
| Finisar-IBM | 850   | 19              | 30              | 25               | 6                   | 2008 |
| CUT     | 850    | 20              | 32              | 25               | 9                   | 2009 |
| CUT     | 850    | 23              | 40              | 25               | 7                   | 2010 |
| CUT     | 850    | 28              | 44              | 25               | 7                   | 2012 |
| CUT     | 850    | 24              | 57              | 25               | 8                   | 2013 |
| CUT     | 850    | 30              | 50              | 25               | 3.5                 | 2015 |
| TU Berlin | 850  | 20              | 30              | 25               | 6                   | 2009 |
| TU Berlin | 850  | 20              | 30              | 25               | 6                   | 2009 |
| UIUC    | 850    | 21.2            | 40              | 20               | 4                   | 2014 |
| UIUC    | 850    | 29.2            | 57              | 25               | 5                   | 2016 |
| NCU     | 850    | 22.4            | 40              | 25               | 4                   | 2015 |
| NCU     | 850    | 36              | 41              | 25               | 8                   | 2015 |
| UCSB    | 980    | >20             | 35              | 20               | 3                   | 2007 |
| TU Berlin | 980  | 44              | 25              | 6                | 2011 |
| TU Berlin | 980  | 24.7            | 50              | 25               | 3                   | 2014 |
| TU Berlin | 980  | 26.6            | 52              | 25               | 6                   | 2016 |
| TU Berlin | 980  | 35.5            | 50              | 25               | 3                   | 2018 |
| CUT     | 1000   | 33              | 50              | 25               | 4                   | 2017 |
| NEC     | 1100   | 20              | 30              | 25               | 4.9                 | 2006 |
| NEC     | 1100   | 24              | 40              | 25               | 6                   | 2007 |
| NEC     | 1100   | 24              | 40              | 25               | 6                   | 2008 |

The 850nm VCSEL is usually used in the short-distance communication and optical interconnection. At first, 850nm VCSEL for a 8μm oxide aperture reached a bandwidth of 15.4GHz and bit rate of 20Gbps in 2001. And then, Finisar and IBM group gained a VCSEL with bit rate of 30 GHz in 2008. In 2009, CUT and TU Berlin invented VCSEL with data rate of 32 GHz and that of 40GHz respectively. The bandwidth of 850nm VCSEL first reached 23 GHz at 25°C with oxide aperture of 7μm in 2010 by CUT. In 2015, error-free bit rate at 50 Gbps was demonstrated by CUT with bandwidth of 30GHz. This VCSEL has a GaAlAs-based micro-cavity and an InGaAlAs-based active layer. And the DBR is proper graded into some compositional profiles. Figure 3 shows the relationship between bit error rate (BER) and received optical power in different data rate. The VCSEL with bandwidth of 29.2 GHz and data rate of 57 Gbps at 25°C was achieved later by UIUC. The cavity length of this VCSEL is half wavelength. And there are 5 quantum wells in active layer which are made of In0.07Ga0.93As/Al0.37Ga0.63. Figure 3 also shows the relationship between bit error rate (BER) and received optical power in different temperature.

Figure 3. Experimental result of 850nm VCSEL [3]
In addition, there are some development of 980nm to 1100nm wavelength VCSEL. In 2007, UCSB developed a 980nm VCSEL with 35 Gbps data rate at 20℃. After that, 44 Gbps data rate VCSEL was invented by TU Berlin in 2011 in the wavelength of 980nm. This team demonstrated a VCSEL with 50 Gbps bit rate, 24.7 GHz bandwidth link in 2014 and VCSEL with 52 Gbps bit rate, 26.6 GHz bandwidth link in 2016. Later in 2018, 35.5 GHz bandwidth with 3μm oxide aperture was gained in 2018. And this was achieved by decreasing the diameter of oxide aperture and thickness of cavity to reducing the mode volume. Meanwhile, DBR was made to be linear grading and the top DBR’s coupling periods were declined to around 14.5. Figure 4 shows the result of this experiment.

In 2017, a 1060nm VCSEL with 22GHz bandwidth and 50Gbps data rate was demonstrated by CUT. This was achieved by a half-wavelength thickness cavity. In order to provide a low optical loss and resistance, the top DBR is composed of 20 pairs of Al$_{0.9}$Ga$_{0.1}$As/GaAs. Bottom DBR is composed of 24 AlAs/GaAs and 5 Al$_{0.9}$Ga$_{0.1}$As/GaAs pairs which can decline the thermal impedance. All pairs in DBR contain compositional intermediate stratum and with doped modulation. In active layer, InGaAs/GaAsP instead of InGaAs/GaAs is used in quantum wells. Some oxide layer are added above the Al$_{0.98}$Ga$_{0.02}$As primary oxide apertures (see Figure 5). The Al-content in surrounding layer is decreased and the thickness of primary layer is also reduced (20nm), which can lead to a high capacitance. Figure 6 shows the final result of this experiment relationship between bit error rate (BER) and optical modulation amplitude.

Figure 4. Experimental result of 980nm VCSEL [4]

Figure 5. Structure of 1060nm VCSEL with bandwidth of 22GHz and bit rate of 50Gbps [5].

Figure 6. Experimental result of 1060nm VCSEL [5].
In the early years, there were some 1100nm VCSEL studies conducted by NEC. They first made VCSEL with 20GHz bandwidth and 25 Gbps bit rate in 2006. And in 2007, bandwidth of 24GHz and data rate of 30Gbps was found through experiment. Finally, NEC demonstrated a 40Gbps error-free bit rate VCSEL with 6μm oxide aperture, which was based on strained three In_{0.3}GaAs-GaAs quantum wells (QWs). This VCSEL can achieve both high reliability and high speed. Top DBR is composed of 23 C-doped GaAs-Al_{0.9}GaAs pairs. And 44.5 Si-doped GaAs-Al_{0.9}GaAs pairs from the bottom DBR. In order to restrict the self-heating effect, NEC introduced the type-II tunnel junctions (BTJ) which could reduce the parasitic capacitance of VCSEL. BTJ is applied above the active layer (see figure 7). Figure 8 shows the final result of this experimental relationship between bit error rate (BER) and receiving power.

![Figure 7. Structure of BTJ-VCSEL [6]](image)

![Figure 8. Experimental result of 1100nm VCSEL [6]](image)

### 3.2 Modulation properties of VCSEL at high temperature

A high temperature can sharply decline performance such as bandwidth and bit rate. The temperature is inevitably high in HPC during data transmission. However, the advantage of VCSEL is that it can keep its performance under this condition. Table 2 shows some properties of VCSEL at high temperature. So far, great progress has been made on 850nm and 980nm VCSEL. In 2018, VIS developed 850nm VCSEL which can work at 150℃ with data rate of 25 Gbps. Besides, 980nm VCSEL with 30 Gbps bit rate at 120℃ was demonstrated by TU Berlin in 2011. In 2017, CUT developed 1060nm VCSEL with bit rate at 40 Gpbs and bandwidth at 16GHz at 85℃.
Table 2. Bandwidth and Bit Rate of VCSELs at high temperature by Back-to-back data transmission

| Group   | λ (nm) | Bandwidth (GHz) | Bit Rate (Gbps) | Temperature (°C) | Oxide Aperture (µm) | Year |
|---------|--------|-----------------|-----------------|-----------------|---------------------|------|
| Finisar | 850    | 10              | 14              | 95              | 8                   | 2012 |
| Encore  | 850    | 16              | 28              | 85              | 7.5                 | 2013 |
| CUT     | 850    | 21              | 40              | 85              | 7                   | 2013 |
| IBM-CUT*| 850    | 21              | 50              | 90              | 6                   | 2015 |
| UIUC    | 850    | 24.5            | 50              | 85              | 5                   | 2016 |
| NCU     | 850    | 22.4            | 34              | 85              | 4                   | 2013 |
| NCU     | 850    | 20              | 41              | 85              | 8                   | 2015 |
| VLS     | 850    | 25              | 150             | 4               | 2018                |
| VLS     | 850    | 25              | 130             | 4               | 2018                |
| TU Berlin| 980   | 11              | 20              | 120             | 3                   | 2008 |
| TU Berlin| 980   | 38              | 85              | 6               | 2011                |
| TU Berlin| 980   | 30              | 120             | 6               | 2011                |
| TU Berlin| 980   | 23              | 46              | 85              | 5                   | 2014 |
| TU Berlin| 980   | 38              | 85              | 5.5             | 2014                |
| TU Berlin| 980   | 35              | 85              | 3               | 2016                |
| TU Berlin| 980   | 24.5            | 50              | 85              | 6                   | 2016 |
| CUT     | 1060   | 16              | 40              | 85              | 4                   | 2017 |

*With tap feed forward equalization driver.

3.3 OOK modulation and PAM4 modulation

All the data in the above table are obtained by On-Off-Keying (OOK) modulation in back-to-back data transmission. OOK modulation is also known as binary amplitude keying (2ASK), which controls the opening and closing of the sinusoidal carrier with a unipolar non-return to zero code sequence.

Four-level pulse amplitude modulation (PAM4) uses four different signal levels to do data transmission, which means PAM4 modulation can transmit 2 bits of information in a symbol cycle, so losses on the transmission channel can be reduced. Based on this advantage, PAM4 modulation has become an inevitable trend.

The eye diagrams of these modulation methods are shown below. As a light source, VCSEL often uses these methods for amplitude modulation in data communication.

![Eye diagram by OOK and PAM4 modulation](image)

4. DISCUSSION

4.1 Challenge for VCSEL in data communication

Because of the increase of VCSEL modulation speed, higher bandwidth of multiple mode fiber link is needed to match it. PAM4 is a popular solution for higher-order optical link modulation with high baud rate, but there are some difficulties in modulating VCSEL in multiple mode links directly. For example, it is hard to solve the limitation of modulating relaxation-oscillation frequency of VCSEL at a high temperature. In order to solve this problem, more research need to be done on how to improve the thermal resistance of VCSEL to decline the temperature, as well as how to improve the encapsulation to reduce the heat effect which can make progress on VCSEL performance.
4.2 Expectation of VCSEL in data communication
In the future, VCSEL is still the main Laser source in data communication. Also it can be used in optical interconnect. It is possible to improve the bandwidth and bit rate of the Next generation VCSEL at high temperature. The development of the modulation method for VCSEL will continue in the future. Besides, VCSEL and PIN-PD can be integrated into a chip in the vertical direction. Based on this chip, the photoelectric decoupling and transceiver integration in optical communication link are completed [8]. This can be well applied in future data communication.

5. CONCLUSION
VCSEL has the characteristics of easy integration, low threshold current and high performance, which makes VCSEL have many applications in data communication. So far, there has been lots of research and progress regarding improving the performance of VCSEL. However, there are still some difficulties that can be focused on in the future, in the modulation of VCSEL-based links directly. It is hoped that relevant research can make progress in the near future. This paper just focus on VCSEL’s modulation properties. So the introduction of VCSEL in data communication is not comprehensive. Further and more comprehensive research is under way.

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