# Market Analysis for Optoelectronic Transceiver in Short Range Data Transmission



By

Jia Luo

B. S., Optical Science and Engineering
Fudan University, 2006

SUBMITTED TO THE DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING IN MATERIALS SCIENCE AND ENGINEERING

AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2008



Signature of Author: ______________________________
Department of Materials Science and Engineering
August 8, 2008

Certified by: ______________________________
Lionel C. Kimerling
Thomas Lord Professor of Materials Science and Engineering
Thesis Supervisor

Accepted by: ______________________________
Samuel M. Allen
POSCO Professor of Physical Metallurgy
Chair, Departmental Committee on Graduate Students

# Market Analysis for Optoelectronic Transceiver in Short Range Data Transmission

By

Jia Luo

Submitted to the Department of Materials Science and Engineering
on August 8, 2008 in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering in
Materials Science and Engineering

**Abstract**

With the increasing demanding of bandwidth in information technology, electronic connections meet the limitation in high speed processing in shorter and shorter reach. In the work, three markets for optical connection with different reach, which range from 10km down to 1 meter, have been discussed.

The 10km market denotes for the LAN standard and would mature soon. For the 100m range, active cable has emerged to meet the requirement and would penetrate the market soon. The detail analysis would be addressed on 1-10 meet market, where electronic cables have just met the limitation. Cost modeling and business plan has been conducted. After that, the conclusion and suggestions would be made on that reach.

Thesis Supervisor: Lionel C. Kimerling
Title: Thomas Lord Professor of Materials Science and Engineering

## Acknowledgement

It is an amazing year for me to study in MIT. On the one hand, so much lectures and assignments make the time limited. On the other hand, jogging along Charles River and different kinds of activities enrich the relaxing hours. All of these would be memorable in my life. However, the most exciting thing is to meet and communicate with all sorts of smart and hard working people.

Here, I really need to present my appreciation for some people in guiding and helping my thesis. At first, I want to thank my supervisor, Prof. Kimerling. Not only because of the instruction on the topic, would the kindness and encouragement through e-mails also help me in the future. And, of course, I earned a lot from the interesting project. I want a program related to photonic devices and I got it. I want a topic not focusing on scientific research too much and I obtained it as well. Thank you so much, Prof. Kimerling.

Secondly, I want to thank Mr. Tremont Miao, who guided me on the technique part. The call as well as the quick reply via e-mails explained the whole industry very clear. Without these, it would be a big problem for me to finish the work.

Then I would like to thank Prof. Chua Soo-Jin in NUS. Although the time would be short for the conversation, Prof. Chua pointed out many method of improvements directly and the way to carry on.

Last but not lease, I want to thank Yuyan, Kwan Wee, Kunal, Manyin, Fidelia and all other classmates for both information on my thesis and the enjoyable time within this year. It is really lucky for me to in the same batch with you. Otherwise, it should be very tough and boring for such a busy year.

At last, I need to thank my parents and my girlfriend. Besides the encouragement from them, my girlfriend also provided me a lot of useful suggestions and supported my work all the time. All of these made me confident in finishing the work.

Thanks to all.

# Table of Contents

# Chapter One: Introduction

With the booming of Information Technology in twentieth century, it is hard to image living without computer, even internet connection nowadays. On the other hand, because of the increasing demand of data transformation, higher and higher bandwidth is required in all kinds of application, such as security control in company networking, advanced resolution in entertainment devices. On the way towards larger and larger bandwidth, current electronic based technology has met the limitation, for example, RC delay between each connector, power consumption caused by induction and radiation.[1] Hence, the adoption of optical fiber appear from long distance communication gradually down to the transmission within several meters. As we can see, the telecommunication between the continents is realized by optical fiber only and people are using optical based technology into Ethernet nowadays. All of these replacements happened because electronic devices cannot provide the transmission capacity. The graph below shows the capacity for data transmission between electronic connection and optical connection.[2]

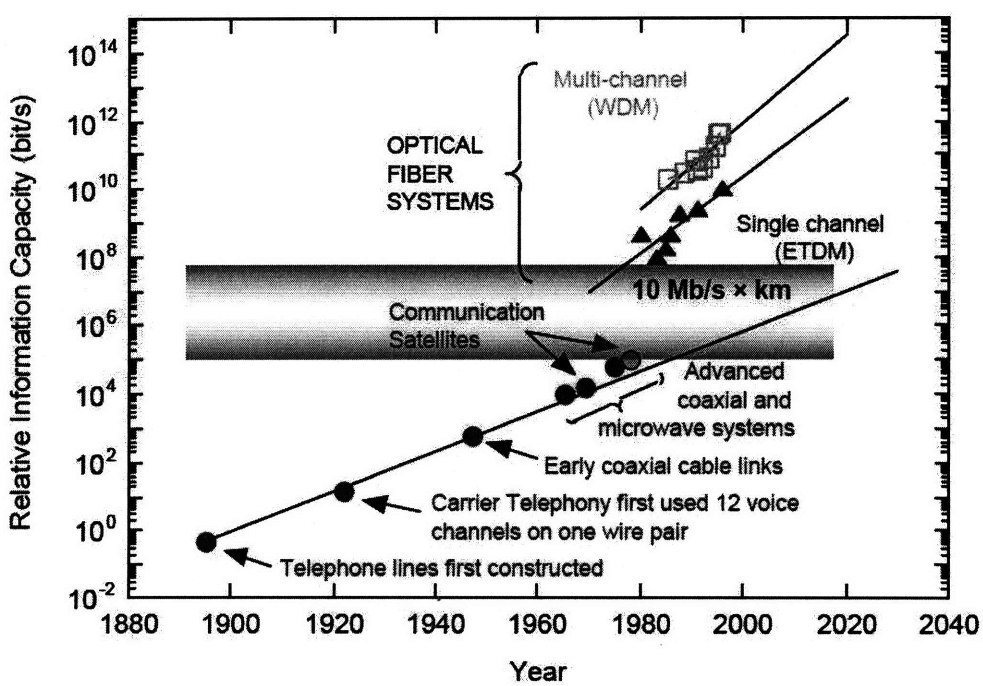


Fig. 1.1 Bandwidth Difference between Electronic Connection and Optical Communication.

With the high bandwidth distance product, the optical components have already shows the ability in communication over long distance above 1 kilometer. Furthermore, components with high bandwidth are keeping reported. For example, the Line Rate for Fiber Channel has been modified from 1Gbps all the way to 10 Gbps within 10 years. Also, the laser and PIN detector working above 100 GHz have been announced separately. On the other hand, with the packaging technology for parallel transmission, it is no doubt that 100 GHz capacity of optical connection can be realized. Currently, CTR works on the replacement using optical technology into shorter distance which can be illustrated using the following table.[3]

| **Name** | **MAN/ WAN** | **LAN** | **SAN** | **Short Cable** | **Inter PCB** | **Intra PCB** |
|---|---|---|---|---|---|---|
| **Length (L)** | >1km | ~1km | 10-300m | 1-10m | 0.3-1m | <0.3m |
| **Standard** | Internet Protocol | Ethernet | Fiber Channel | Developing | Developing | Developing |
| **Use of Optics** | since 1970s | since 1980s | since 1990s | <2013 | 2011-2015 | after 2015 |
| **Mature Market** | until 1990s | until 2000s | ~2010s | N/A | N/A | N/A |
| **Start Speed (F)** | 56Kbps | 10Mbps | 1.0625Gbps | ~10Gbps | N/A | N/A |
| **F*L** | 1 Mbps*km | 10 Mbps*km | 100 Mbps*km | 0.1 Gbps*km | N/A | N/A |

Table 1.1 Specifications for market with different reach.

According to the graph, the substitution process would undergo first adoption, further improvement and then achieve mature market. This work would focus on the distance ranging from LAN to short cable. By discussing the mature market, LAN, and SAN, which needs further improvement, the analysis and prediction of Short Cable area would be addressed in detail. The start speed for optical connection in Short Cable is set as 10Gbps since USB 3.0, which aims at 4.8 Gbps is under research nowadays and would be commercialized soon.

Nevertheless, as mentioned before, the higher transmission speed can already be obtained if parallel components are packaged together.

# Chapter Two: Technology Overview

As discussed above, the replacing process would happen gradually from long distance range to short distance, which means there would be a long period when both electronic and optical components coexist. Since the signal transferred on these two kinds of connections are totally different, high and low voltage versus magnitude of light, the communication between them remains to be the key problem. Currently, the signal would be modulated into the other form by optoelectronic transceiver.

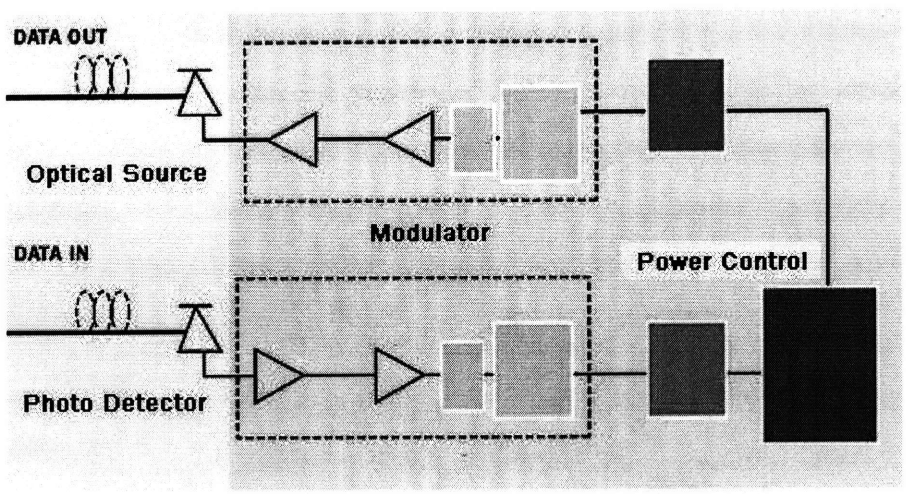


Fig. 2.1 Structure for Typical Transceiver.

Basically, a transceiver consists of four parts, optical source, photo detector, electronic modulator and power control. When the optical signal is transferred from an optical fiber to transceiver, the photo detector would receive the light and change the optical variants into voltage variants into the circuit. On the other hand, when the electronic signal comes in, the modulator would dictate the optical source and send out the correct data. Hence, the signal is switched between two forms. The electronic modulator and power control, which is just the circuit, can be easily realized by current electronic technology. The key consideration lies in the optical part, both optical source and photo detector. On the other hand, since transceiver also stands for the combination of electronic and optical technology, the packaging process appears to be another problem. All of these would be addressed carefully here. The following graph shows the schematic diagram for transceiver with parallel devices.

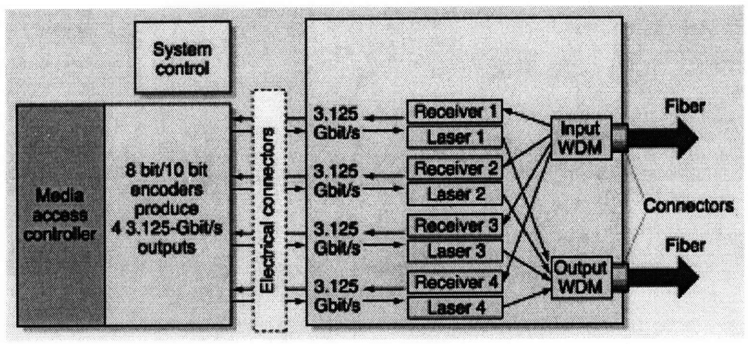


Fig. 2.2 10Gbps Transceiver with 4 Parallel Transmitter and Receiver Pairs of 3.125Gbps each.

The current technology has proved the transmission capacity with 10Gbps each, which means the 40Gbps in total.

## 2.1 Optical Source: Laser Technology

The purpose for optical source is to translate the electronic signal into optical light, which fulfill the job in transmitter. Due to the advanced technology of semiconductor industry, current semiconductor laser diode, which can be fabricated consisting with standard CMOS integration process, is used as optical sources. And this provides the convenience for adopting optical connections in short range transmission. LED[12], Edge-Emitting Laser (EEL)[13] and Vertical Cavity Surface Emitting Laser (VCSEL)[14] are the three players.[15]

| Specification | EEL | VCSEL |
|---|---|---|
| **Application** | Telecom | Datacom |
| **Active Region Confinement** | 300*400*0.07 | 3*3*0.07 |
| **Modulation Frequency** | 20GHz | 120GHz |
| **Threshold Current** | 20mA | 0.5mA |
| **Output Power** | 45mW | 0.17mW |
| **Power Efficiency** | 0.89A/W | 11.76A/W |

Table 2.1 Key parameters for optical sources.

Since the modulation frequency of LED is too slow for the communication in short range, the table above only shows the relationship between EEL[16] and VCSEL. Since the attenuation is relatively small in optical fiber, the key consideration for optical source in short reach transmission would be the threshold current and the modulation frequency. Both of them are determined by the size of active region. With decreasing the active layer, the loss would be small, therefore, threshold current is reduced and the transmission frequency would increase significantly.[17] Hence, the modulation frequency would be higher for VCSEL than EEL. And the currently 100 GHz transmission rate with single optical source has been reported using VCSEL structure. For three kinds of light sources, the key difference is due to the confinement of the active layer, which controls the volume of it. All of three structures would be discussed next.[18]

### 2.1.1 Light-Emitting Diode (LED)

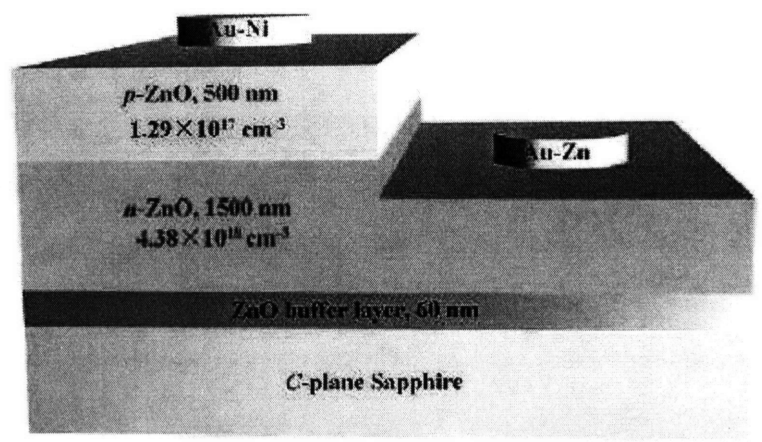


Fig. 2.3 Advanced LED structure.

As showed above[19], LED is just a simple pn junction structure. When current goes through the layer structure, some electron would be excited into the conduction band while leaving the holes there. When the electron on the conduction band combines with the holes in the valence band, the extra energy is released in the form of photon and hence resulting light.

The key point for LED is the large emitting area. Since there is not any confinement on the structure, the light can come out at any position with all kinds of energy and the production cost can be very low. This leads to the high power output for LED structure although the efficiency could be very low. However, the large output makes LED suitable for the application in the area requiring high intensity, such as lighting and large screen display. On the other hand, this also results in main disadvantage in high frequency modulation, which is the alternative for electronic technology. Such a wide range of light leads to the difficulty in reaching equilibrium. Thus, the modulation frequency is very slow for this structure.

### 2.1.2 Edge-Emitting Laser

In order to increase the modulation frequency, the emitting area should be confined. Thus, the threshold current can be reduced.

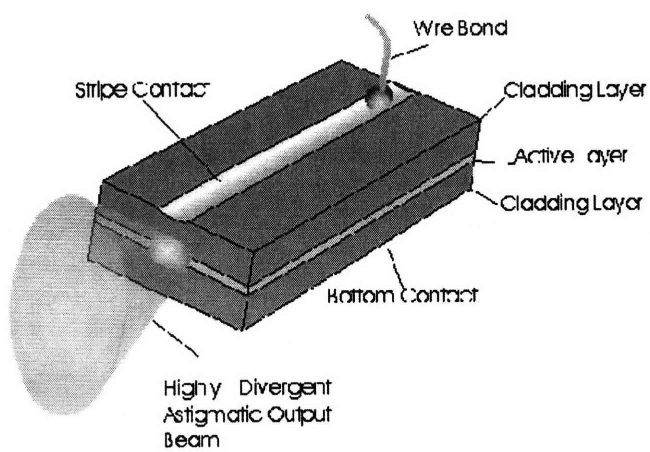


Fig. 2.4 Structure for Edge Emitting Laser

The above picture shows the basic layer structure for Edge-Emitting Laser. An active layer is sandwiched by the cladding layers. Usually, the active region would have a smaller bandgap compare to the confined layer. And certain layer would be deposited in the side of active layer for current confinement in lateral direction. With the current confinement, the spectral distribution is narrowed and the device can be switched faster. Similar to LED, the active region is not too small to provide high power supply. However, this also leads to the relatively higher power output than VCSEL. With both considerations in power output and modulation frequency, this is the current technology for Telecommunication.[20]

On the other hand, again, the large active area compare to VCSEL makes edge-emitting laser slower. Furthermore, since the light comes out on the edge of laser diode, it is hard to get the high integration rate.

### 2.1.3 Vertical Cavity Surface-Emitting Laser (VCSEL)

Since one of the key concern in short range transmission is the modulation frequency, the practical structure is VCSEL and small threshold current consist with the small active area has been realized in VCSEL structure.[21]

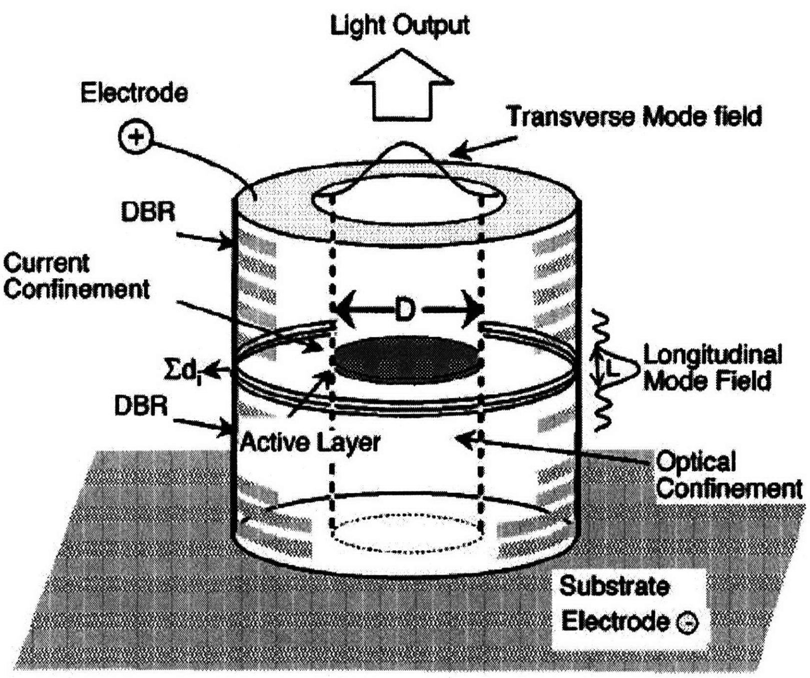


Fig. 2.5 General Structure for VCSELs.

According to the picture, the active layer is sandwiched by two Distributed Bragg Reflectors (DBRs). With the highly selectivity of DBR mirror, the line width can be decreased to several Angstrom. The active area is further reduced by lateral oxidation confinement. Usually, the active layer contains only several quantum well structures. By this technology, the threshold current can be reduced to as low as several $\mu A$. And the modulation frequency of 100 GHz has been realized.[22]

On the other hand, another benefit from this structure would be the high integration rate. The lateral area is in the range of tens $\mu m$ times tens $\mu m$, which shows the potential in parallel processing. The later discussion on packaging provides the technology in increasing the bandwidth in this method.

### 2.1.4 Monolithic Technology

Another key consideration lies in optical source is the size of the transceiver. As one can see, it would be more attractive if the size of transceiver can be decreased simultaneously with the transmission range. And some promising results have been reported recently.[23]

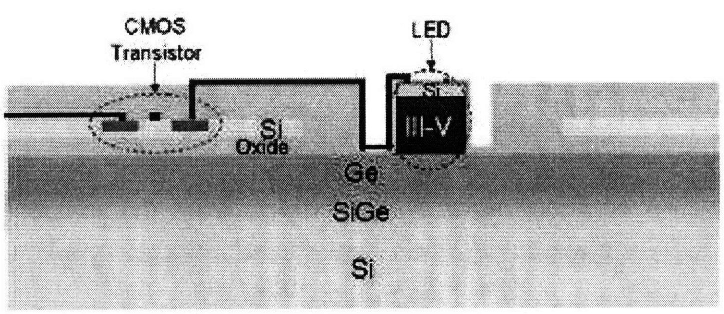


Fig. 2.6 Monolithic Optical Source on Si substrate with CMOS technology.

This device is built on the Si substrate which can be fabricated using traditional CMOS processing techniques. Although only the LED has been realized so far, due to further improvements on the defect aspects, EEL and VCSEL integration is expected.

## 2.2 Detectors for Optical Communication

Detectors demodulate optical signals into electrical variations, which is the key part for receiver. Then the electrical signals are subsequently amplified and further processed. For such applications, the detectors must satisfy stringent requirements such as high sensitivity at operating wavelengths, high response speed, and minimum noise. Furthermore, the detector should be compact in size, use low biasing voltages, and be reliable under operating conditions. Currently, PIN photodiode are most commonly used in optical fiber processing systems.[24]

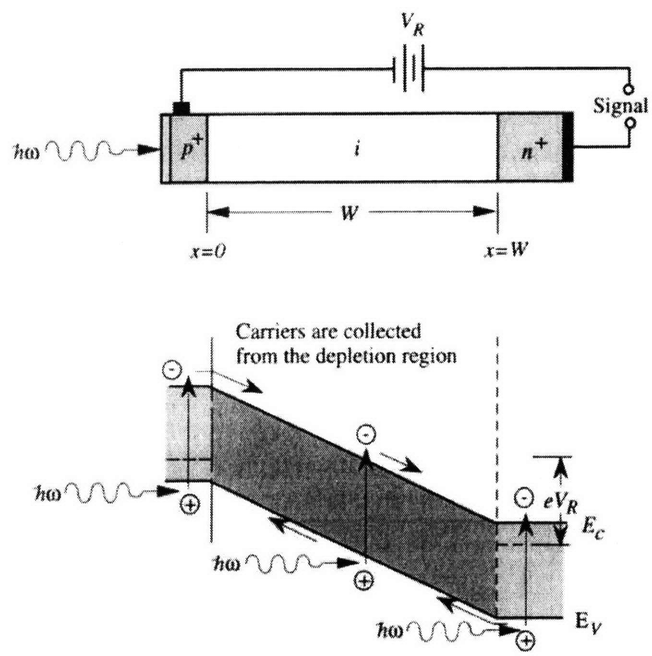


Fig. 2.7 PIN photodetector structure.

Here is the schematic diagram for PIN photo detector.[25] The photon absorbed in the 'i' region would generate electron hole pairs. With voltage bias, they are attracted to opposite direction and cause the electronic variants.

Conventionally, the photo detector is just a Si based p-i-n junction, which limits the modulation frequency due to low electron mobility. Some people pointed out the solution in improving the electronic structure, so called spatial modulated LED (SML). The structure is showed below.[26]

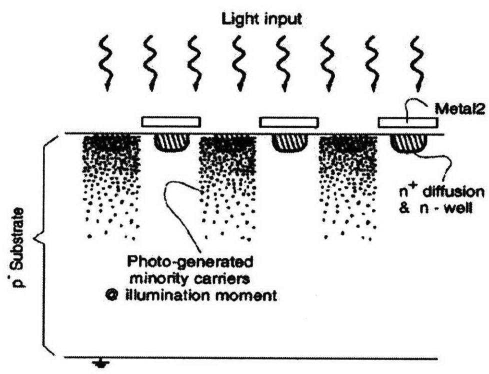


Fig. 2.8 Periodic Structure of Electrodes in SML.

The reason for slow modulation frequency is partially due to the slow diffusive carriers which most excited in the substrate. With the periodic structure, the final signal is produced by subtracting the signal in covered area from that in uncovered place, hence, removing the effects caused by slow diffusive carriers and increase the transmission frequency. Nevertheless, although this can increase the transmission rate, the value cannot reach very high.

Recently, Ge on Si structure is developed to use Ge as the intrinsic layer which aiming at improving the mobility.

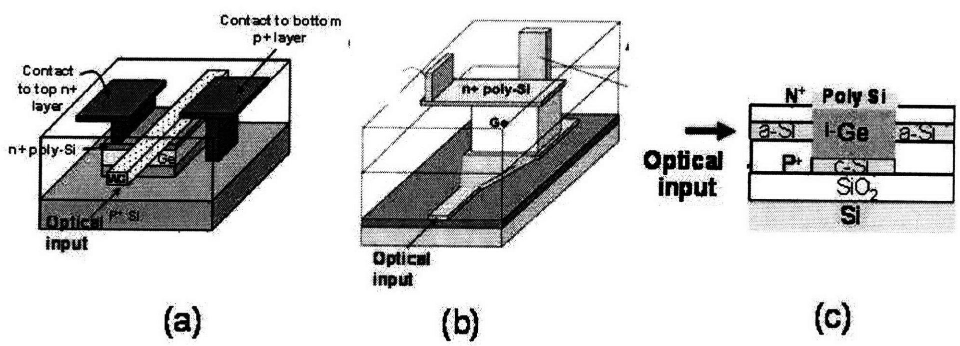


Fig. 2.9 Schematic diagrams showing different waveguide-detector coupling schemes: (a). evanescent coupling, waveguide on top of the Ge detector; (b) evanescent coupling, waveguide at the bottom of the Ge detector; and (c) butt-coupling scheme, output end of the waveguide directly inputs to the detector.[27,28]

This structure handles the mobility problem directly. Since Ge has higher mobility, the modulation rate of 10 GHz has been achieved. This technology is very attractive since it can be fabricated using existing CMOS technology.

| Specification | Ge on Strained Silicon | SML |
|---|---|---|
| **Mechanism** | Higher Mobility | Electronic Signal Control |
| **Operating Frequency** | >10GHz | 3.125GHz |
| **Operating Wavelength** | 850nm~ 1550nm | 850nm |
| **Responsivity** | 0.5A/W | 0.07A/W |

Table 2.2 Comparison of Two Technologies.

The above table shows the improvement caused by both technologies. And higher modulation frequency would be expected if the Ge on Strained Silicon technology can also improves the electronic structure.

## 2.3 Logic and Drive Circuitry

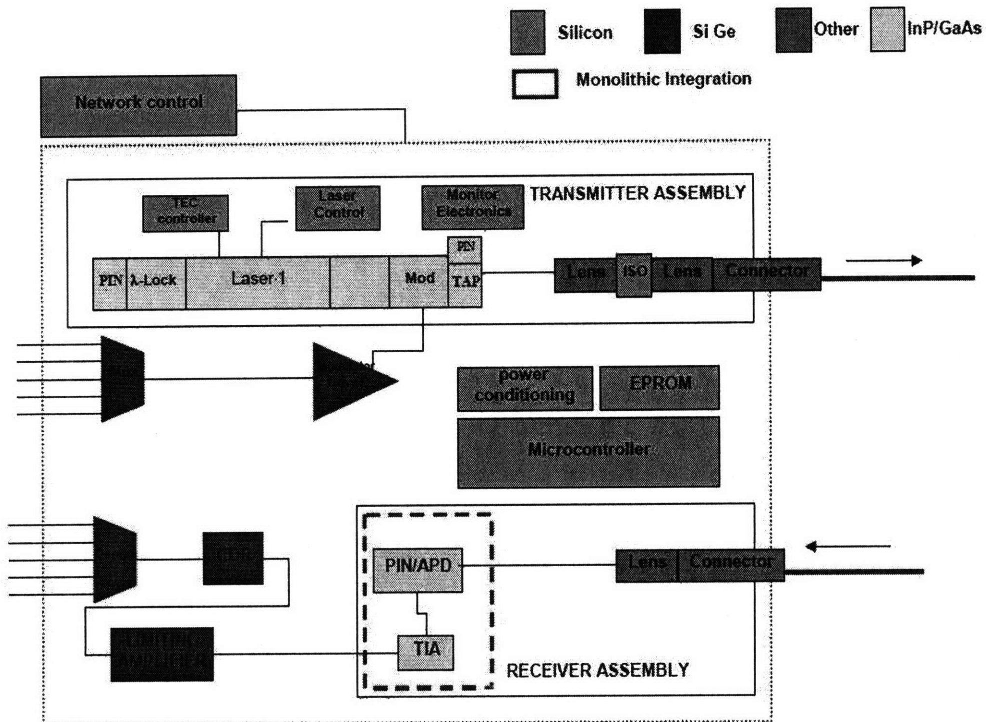


Fig. 2.10 Proposed structure for transceiver packaging.

Electronic modulator and power control units are all deposited on the same chip.[2] The general arrangement and the design are showed above. The amplifier is used to increase the electronic signal obtained from optical fiber.

## 2.4 Packaging Technology

Since all the components discussed above should be aligned and assembled into one small box, this process is very critical for the manufacturing.[29] For the LAN and SAN, TOSA, ROSA standards are adopted to align the products. However, with decreasing transmission length, the suppliers are trying to assemble the transceiver together with fibers, such as active cable. By this means, the size of the product can be reduced and the alignment problem, which causes low yield, would be avoid and the manufacturer only need to handle the electronic part. This can also decrease the cost and it would be the trend for short distance transmission. Below shows the general picture for TOSA and ROSA packaging standard.[30]

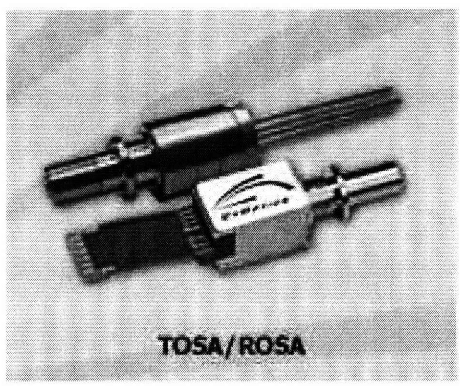


Fig. 2.11 TOSA ROSA subassembly.

Next part would introduce the general packaging process for current commercialized transceiver and the proposed packaging structure which would be adopted as the product in short cable area.

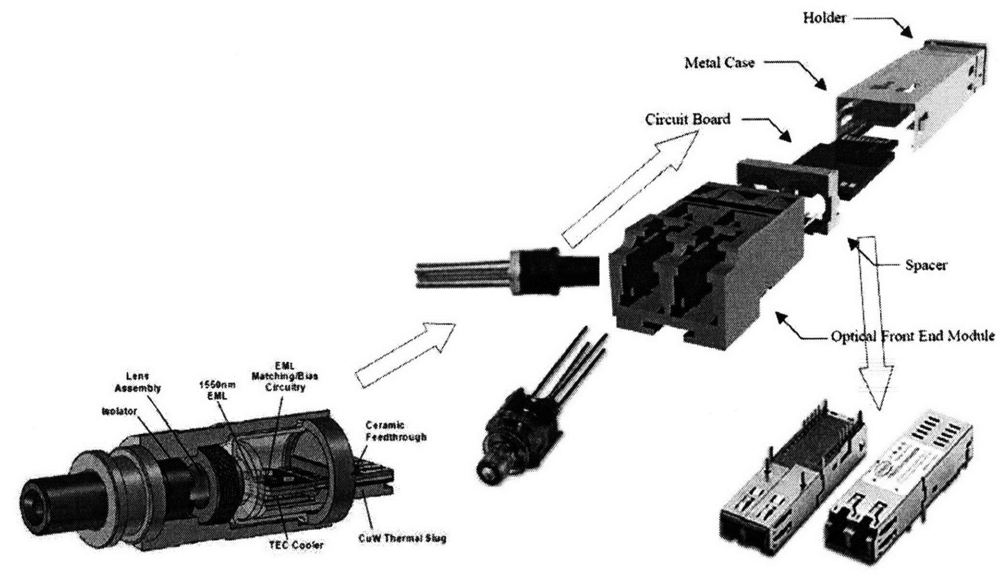


Fig. 2.12 General Packaging Process for Current Transceiver.

Either TOSA or ROSA packaging is produced first and then encapsulated into the discrete optical source or photodetector modules. Finally, all of the components are put on same substrate and form the product.

Another promising packaging technology would be the parallel assembly techniques.[31]

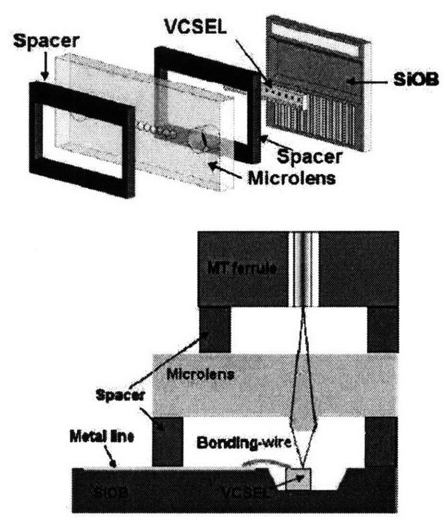


Fig. 2.13 Parallel Packaging of VCSEL.

Since the light of VCSEL comes out vertical to the surface, it would be easy to package them in parallel and 120GHz transmission rate is realized in this structure as mentioned before.[32]

Furthermore, another promising packaging technology would be addressed as MOST standard technique here.

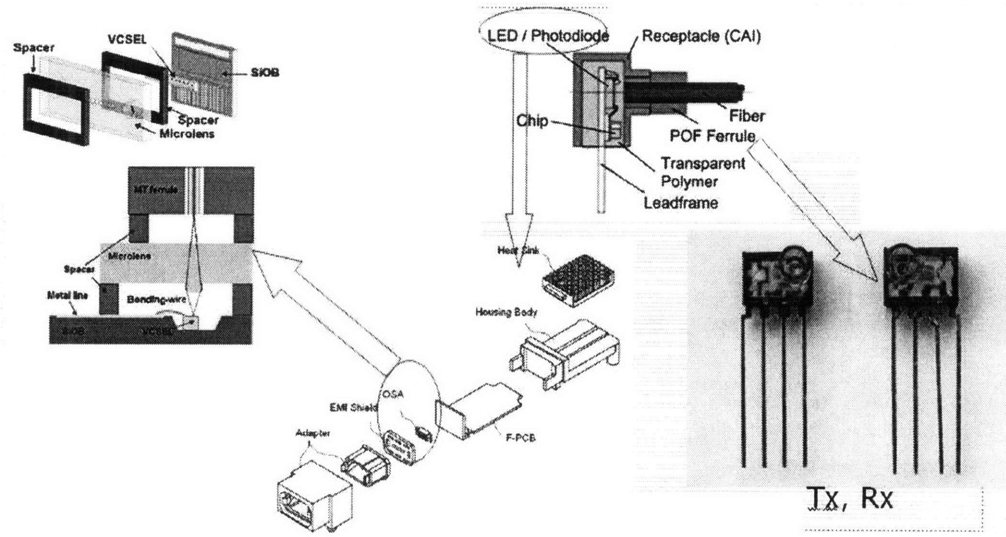


Fig. 2.14 MOST Standard Packaging Process for Short Reach Transceiver.

The advantage for this technique would be the smaller packaging size as the pins are vertical to the optical cavity. And the price would be relatively lower.[10]

# Chapter Three: Optical Communication in LAN

LAN denotes the communication range around 1 kilometer. As discussed in the first chapter, the usage of optics in this area has started in the mid of 1980s and would be mature soon.

## 3.1 Basic Technology

In LAN, Ethernet Standard is adopted. The operation speed has increased from 10 Mbps at first and increase to 10 Gigabyte Ethernet (10 GbE) nowadays. Since the modulation frequency has such a large range, LED is applied for low frequency modulation while VCSEL has come to replace it for large bandwidth. Furthermore, as mentioned before, besides the component variants, packaging results in a lot of possibilities, such as pin numbers, reach, power and so on. All the parameters lead to different design for the final product. And this makes the market analysis important.[4]

| Technique Category | Specification |
|---|---|
| **Network Standard** | SONET/SDH, Ethernet, Fiber Channel… |
| **Form Factor** | XENPAK, XPAK, X2, XFP, SFP+… |
| **Emitter** | VCSEL, FP Laser, LED… |
| **Wavelength** | 850nm, 980nm, 1310nm, 1550nm… |
| **Mode** | SMF, MMF, CWDM, DWDM |

Table 3.1 Variants for Optoelectronic Transceiver

Furthermore, the connector type, reach and other parameters also increase the diversity of the products. This would lead to the fierce competition between all the suppliers for optical connections and finally rule out the small one.

## 3.2 Market Analysis

The analysis of LAN, which has experienced a tough time until mature, would instruct the future penetration of optical components into shorter distance market. Usually, for a young market to mature, it should undergo take off phase, overshoot phase, cooperation phase and standardization phase. The LAN market follows the theory very well.

In the first stage, with the high bandwidth distance product and increasing demands for fast modulation frequency, hundreds of suppliers jump into the market. They provide their own products since the market is so huge that each of them can make profit with only a small share of the market. However, when the market saturates, it turns out that different standard products cannot work with each other and the remaining one have no place to sell. Then the bubble explodes in the overshoot phase and the market shrinks significantly after 2001 and the economics of scale cannot be achieved for each supplier. Thus, the idea of standardization is pointed out and big companies cooperate with each other while the small ones are hard to live. Within these years, a lot of work has been done on the standardization process of transceivers in LAN. Hence, it would be possible to learn the current state of the market by checking the standardization process of transceivers.

| Speed (GB/s) | Avago | Finisar | Emcore | JDSU | Mergeoptics | Total |
|---|---|---|---|---|---|---|
| **0.155** | 149 | 51 | N/A | 4 | N/A | 204 |
| **0.622** | 83 | 37 | N/A | 4 | N/A | 124 |
| **1** | 81 | 21 | 2 | 0 | N/A | 104 |
| **2** | 24 | 53 | 6 | 4 | N/A | 87 |
| **10** | 7 | 18 | 8 | 12 | 30 | 75 |
| **40** | | 1 | | | | 1 |

Table 3.2 Current Standardization state for optical connection in LAN.

The table only shows the current product for 5 major suppliers, Avago, Finisar, Emcore, JDSU and Mergeoptics. It should be mentioned that, during the early time for opto-electronic transceiver, there are around 200 companies with transceiver products. If each has only five products, then the total number would be significant. This means the products for low speed, 155 Mb/s and 622 Mb/s, should have a great variety. On the other hand, since the 40 GHz technology has not been mass produced, the number for 40 GHz product cannot show the real trends for that. However, with the small number of suppliers in the market, it can be concluded that the standardization would be realized soon. The gentle slope of the curve below also shows the standardization has been realized. This means the maturity of market as well as the successful penetration of optical connection in this range.

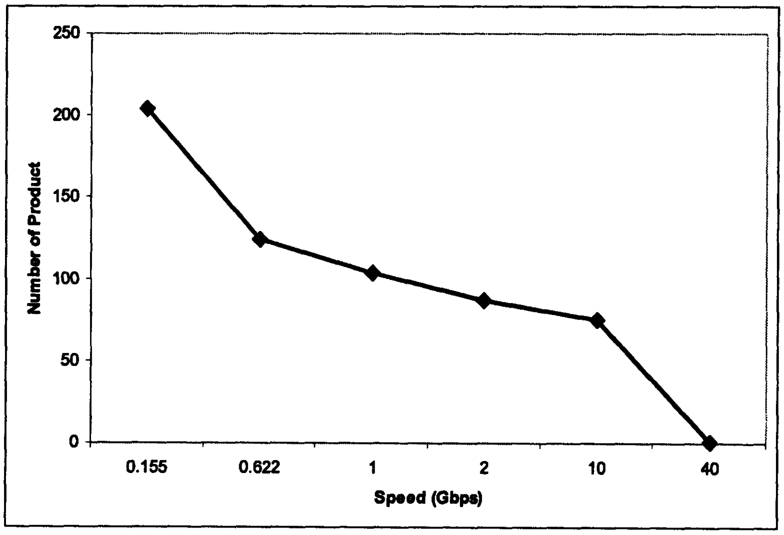


Fig. 3.1 Standardization trend, which shows the mature market.

# Chapter Four: Optical Communication in SAN

Optical connections entered SAN market in mid 1990s, when the electronic counterpart meets the limitation in this area as well. Although it is a younger market than LAN, the cooperation between the suppliers have already been built due to the maturity process of LAN. Thus, a successful penetration of market can be expected.

## 4.1 Technology

Conventionally, the transceivers combined with optical fibers are used to do the job. However, in Auguest 2007, Luxtera reported their Active Cable product, Blazar, which attracts the interest in this field.

Active Cable denotes for the combination of optical fiber and opto-electronic transceiver. One of the biggest problems for transceiver is the alignment problem. Since a small variation between the transmission channel on optical fiber side and the receiver on transceiver would cause a big power loss during the transmission, people paid a huge effort to address it, such as creating standard.[5,6]

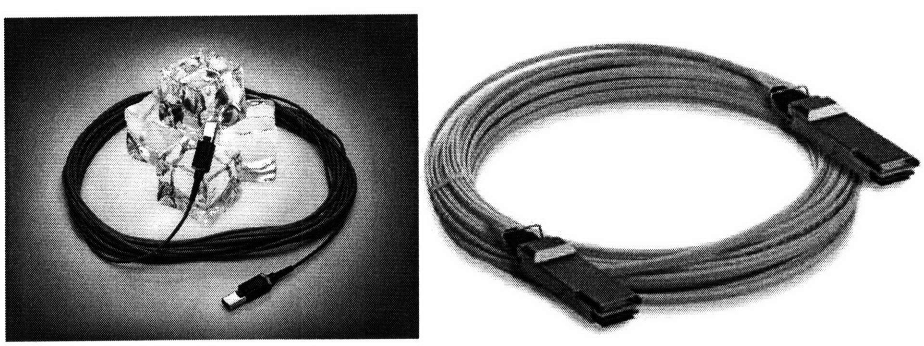

Fig. 4.1, Active Cable products.

However, in active cable, the optical connector would be buried in the assembly with copper wires, which avoids the connection alignment between fiber and transceiver. This technique reduces the cost for optical connection a lot and can get higher bandwidth as well as sufficient reach for SAN. On the other hand, this also predicts the trends for short range optical connection, which is small size with higher integration.

## 4.2 Market

In June 17, 2008, Luxtera Inc., the world leader in Silicon CMOS Photonics, announced that its 40 Gigabit Optical Active Cable (OAC), Blazar, is under evaluation by a number of Tier 1 OEMs in high performance computing, enterprise and proprietary interconnect markets. Luxtera is also showcasing the product in the Mellanox Technologies booth at the International SuperComputing Conference. Enterprise datacenters and HPC users gain 2x throughput and over 3x reach using Luxtera's Blazar versus existing multimode fiber based interconnect. Users also gain 4x density improvement with one QSFP connector taking the same space as four XFP connectors. On the other hand, Finisar also announced their active cable, Laserwire this year. And other companies are working on their own products as well.

Similar to all the other market, the market in this range should also take a period to mature. However, since big companies are all starting to develop the technology of Active Cable and the cooperation would help to establish the standard efficiently, it is reasonable to believe that active cable would penetrate the market with high bandwidth and low cost. Of course, it takes some time, but would be realized follow LAN market.

# Chapter Five: Optical Communication in Short Cable Connection

As mentioned before, with successful penetration in long reach communication market, it is the right time to analysis the market and strategy for the connection in this range. Like the same barrier faced with Ethernet and Fiber Channel, the current electronic connections would be the competitor to optical connections. On the other hand, similar to all the previous market, the optical technology would overtake the electronic devices by the advantages in high bandwidth and low power consumption as long as the electronic connections meet the limitation. This chapter would compare the specifications of optical and electronic devices followed by some consideration of the trends for this market.[33]

## 5.1 Current State for Processing Speed

Usually, all the replacements start when the old technology cannot meet the increasing requirement. Hence, the first thing is to judge the current state for process speed and determine whether the replacement has to be conducted.[1]

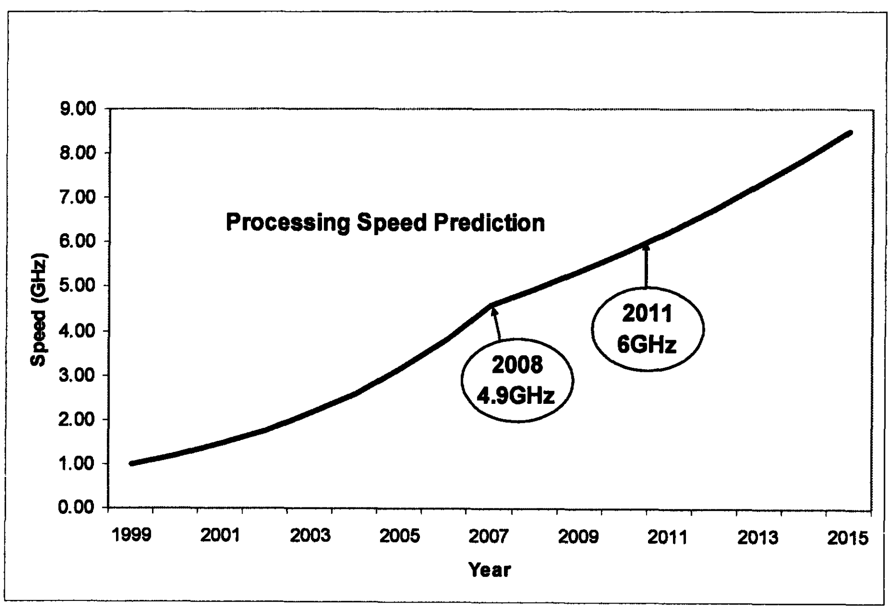


Fig. 5.1 Current state for processing speed.

Based on the prediction of ITRS, the current speed for transmission already reach 4.9GHz and would increase by a 8% CAGR annually. According to the analysis, the processing speed would achieve 6 GHz in 2011.

## 5.2 Limitation for Electrical Based Short Cable

In this distance range, there are several kinds of cables for electrical signal transmission, such as two-wire open line, twin lead, twisted pair[34], shielded pair and coaxial cable[35]. Each of them would have the thermal loss due to the heat dissipation, while some of them also cause high radiation loss and dielectric loss. Among them, coaxial cable has the lowest loss as well as the highest transmission frequency. The latter discussion would base on coaxial cable model.

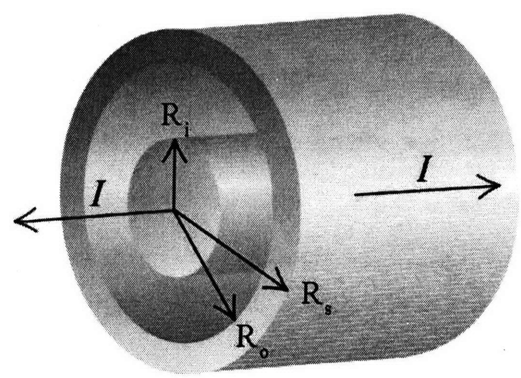


Fig. 5.2 Structure for coaxial cable.

The above picture shows the structure for coaxial cable. The inner conductor is surrounded by dielectric layer, which prevents the leakage current. In order to minimize the radiation loss, another conductor is made to cover the whole inner core. During the transmission, two current with same magnitude but opposite direction pass on the two conductors separately, which shields the electromagnetic wave in the outer space.

For the bandwidth of coaxial cable, the lower cutoff frequency would depend on whether the phase matches with the load while the upper cutoff frequency depends on the power attenuation. Furthermore, with higher frequency, the size of coaxial cable should increase to reduce the resistance due to skin effect. Generally, in order to work on high frequency, the radius of coaxial cable should be increased which would result to the consideration in dimension of the connection. Based on the lossy two conductor transmission line model, including all the consideration above, the bandwidth has been calculated.

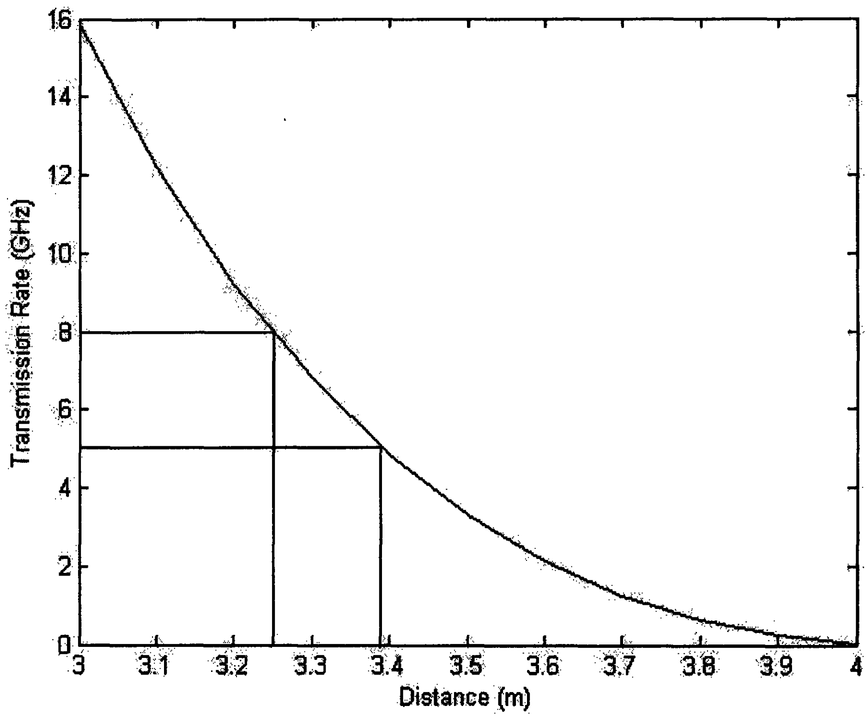


Fig. 5.3 Speed limitation for coaxial cable in short cable range.

According to the simulation, the maximum reach for 5 GHz is less than 4 meters. However, with further increasing transmission rate, the reach would not be affected a lot. The simulation assumes that the loss during the data transfer is 1 dB per meter and the match loss is equal to 1 dB as well. The details would be explained in the appendix. The results may be not exactly correct but it shows the reach of electronic cable has been limited to 4 meter. Without the capacity to meet the higher requirement, the replacement should be taken now.

## 5.3 Specifications for Optical Connection

The case for optical fiber is totally different story. Due to the work in 1970s, the loss of optical fiber can already be omitted in this range and the only limitation for the bandwidth is due to dispersion. However, the dispersion problem would not limit the bandwidth under well usage.[8]

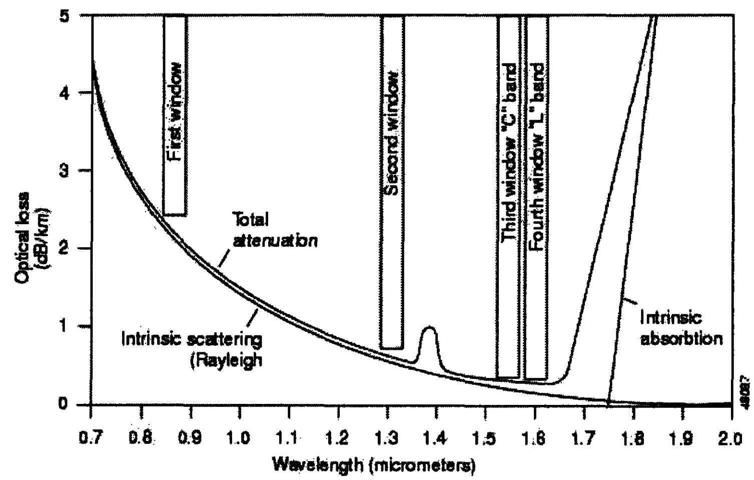


Fig. 5.4 Loss on optical fiber.

The detail would be discussed in the appendix.

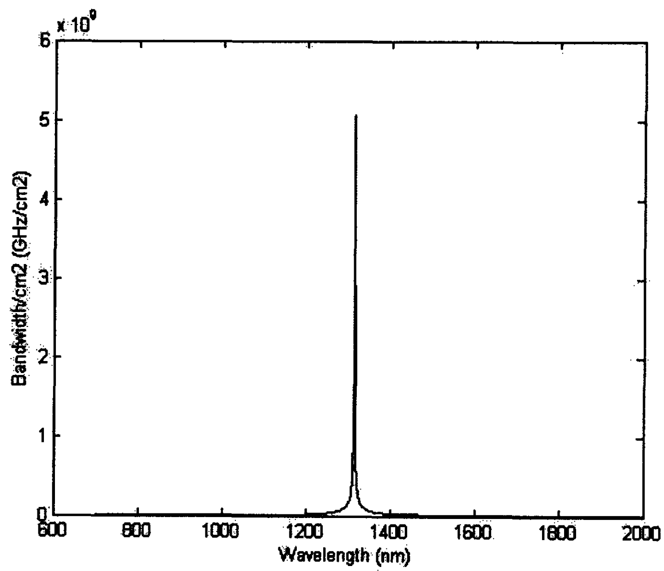


Fig. 5.5 Speed limitation for optical fiber, $10^8$ larger than coaxial cable.

The general bandwidth of optical fiber can be showed below. The ideal limitation for optical fiber would be above $10^9$ GHz/cm$^2$. However, the commercialized product would not function in the maximum value. Nevertheless, the bandwidth for commercialized optical fiber can reach $10^6$ GHz/cm$^2$ easily. The following graph shows the bandwidth in current used three wavelength range.

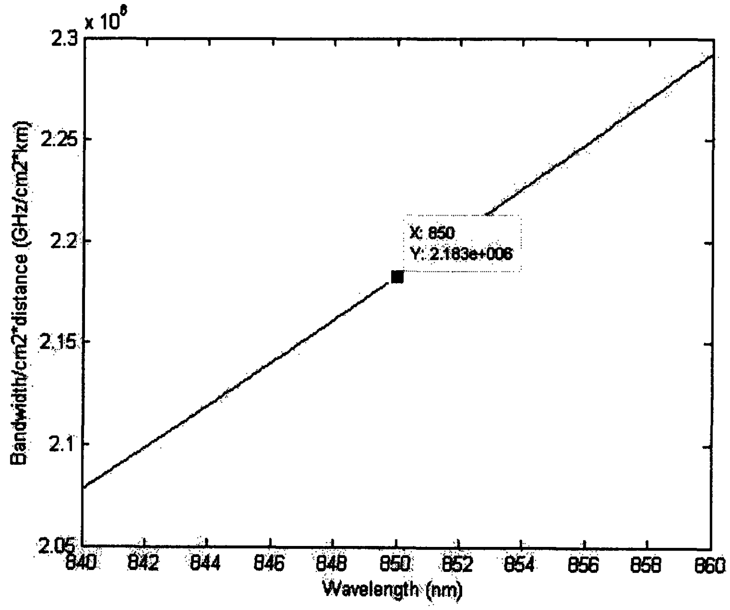


Fig. 5.6 Bandwidth/cm$^2$ of optical fiber in 850nm window.

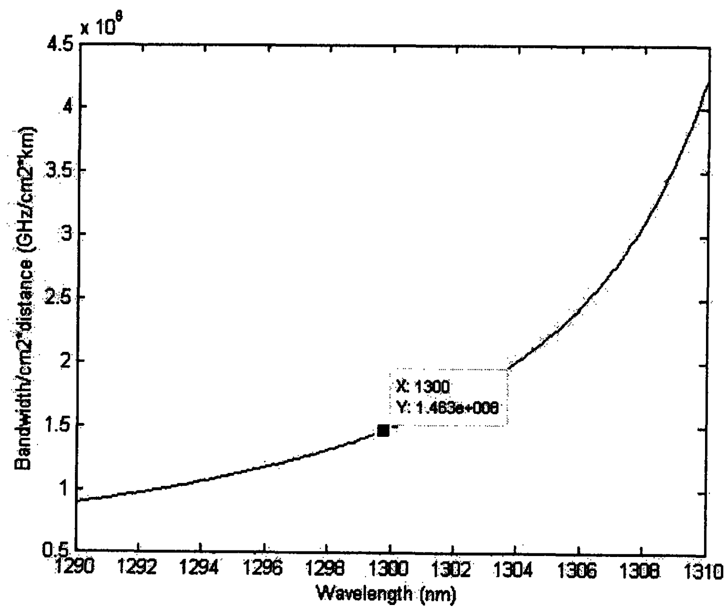


Fig. 5.7 Bandwidth/cm$^2$ of optical fiber in 1330 nm window.

## 5.4 Peripheral Component Interconnect (PCI) express standard

PCI is the standard for interconnection between PCB with the peripheral components. First PCI standard is designed to support a data rate 250 Mb/s in each direction.[36] Generally, 8 lines would be used in parallel to provide a 2 GB/s speed although 16 lines would be install together. The PCI bus has served us well for the last 10 years and the next generation, called PCI express has been released in 15$^{th}$, Jan. 2007, which double the speed of PCI standard. In order to meet the explosive demand for high processing speed, PCI express 3.0, aiming to double the speed of PCI express, is under research and the final specification is due in 2009.

PCI express is an electronic based standard which can easily reach the limitation of coaxial cable.[37] This builds a large barrier for optical counterpart to penetrate the market. However, PCI express 3.0 would include transmitter and receiver component to meet the requirement for high process speed. The PCI SIG predicts that 'final PCI express 3.0 specifications, including form factor specification updates, may be available by late 2009, and could be seen in products starting in 2010 and beyond.'[9]

## 5.5 Opportunity for Optical Short Cable

Since the electronic cable would face the limitation in this distance range soon, the optical alternative would be adopted here. However, currently, there is no such a huge market to reach economic of scale for optical connection. The best strategy is waiting for the release of PCI express 3. With the usage of optics in the back plane, the economics of scale can be achieved easily and the products can be mass produced. One of the specific alternatives would be optical based USB. The next chapter would analysis the USB market when the economics of scale is achieved.

# Chapter Six: USB Market Analysis

Following the above discussion, USB standard would be one way to start the replacement in 1-10 meters data transmission. This chapter would address the optical based USB market when PCI express 3 is released and it is based on optical standard.

First of all, because of PCI express, it would be very difficult for optical component to penetrate into the market, which is 5 GHz within 3 meters. The possible way would be achieving the higher speed, like 8-10GHz in 1-3 meters, or longer distance as 5 GHz in 5-10 meters. On the other hand, currently, there is no huge market for high transmission requirement, like 5 GHz in 5-10 meters, which is not sufficient to reach economics of scale. For the distance longer than 10 meters, active cable already realized the application. Hence, the reasonable way for optical standard USB port would be achieving 5 GHz and waiting for the release of PCI express 3. With the integration of optical based port on the back plane, the economics of scales can be achieved easily. The following analysis would address the standard on 5 GHz specification and the technology is already there.[9]

The other key consideration would lie on the packaging method of optical USB port. In order to fit the size of current USB port, the packaging cannot adopt the same way as used in LAN or SAN, which is usually 5 cm in length. Two methods for packaging would be discussed here and followed by the business plan.

## 6.1 Packaging Technology

### 6.1.1 MOST standard

MOST, Media Oriented Systems Transport, a communication system is developed to meet the entertainment, road guidance and some other requirements in automotive industry. It has specified all kinds of media details in the car for the convenience of car producers.[10]

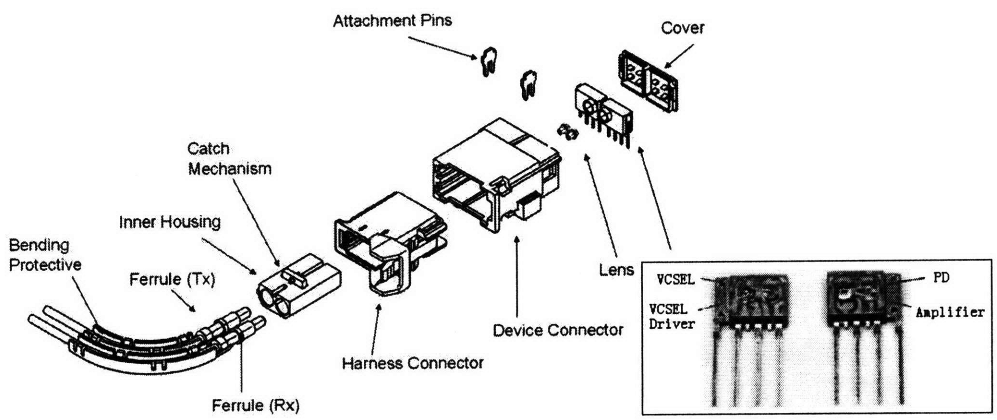


Fig.6.1 MOST standard packaging method.

The above shows the structure and process of MOST standard for optical connection in the car. In that case, the reach would be around 20 meters, which is just nice for the target here. The optical Transmitters and Receivers are packaged separately on the substrate with IC chip for control as well as 4 pins for connection. Then they would be aligned and assembled to form a standard port. Finally, the pins would be attached to the PCB and come out the product. However, the transmitter and receivers used here is LED and low frequency PIN detectors, which is just for low speed modulation. For the USB port here, VCSELs and advanced technology of photo detectors would be adopted in the package and increase the modulation frequency.

### 6.1.2 Monolithic Method

Another packaging method would base on the monolithic deposition technology of silicon and III-V material. A lot of researches have been done on fabricating III-V materials on silicon wafer, which would combine two most advanced technologies and increase the integration rate.

Currently, deposition of III-V LED on silicon wafer has already been approved as discussed before and the results can be illustrated below.[38]

| Specification | Technology | Practical Value | Research Value |
|---|---|---|---|
| **Optical Source** | VCSEL | 12.5 GHz | 120 GHz |
| **Photo Detector** | Ge-Si | 7 GHz | 20 GHz |
| **Packaging** | Discrete | 120 GHz | Not Reported |

Table 6.1 Specifications for Current Technologies.

As mentioned before, although VCSEL on silicon wafer has not been realized yet due to large defect density, this would probably happen within 5 years. And higher bandwidth can be achieved by improving electronic circuits. Furthermore, the packaging technology for parallel devices has been reported, which shows the easy way to double or triple the transmission rate. Hence, it is reasonable to propose the monolithic based packaging here.

## 6.2 Cost Modeling

Based on the two packaging models, a simple cost modeling of the products is conducted. The data list is illustrated in details in appendix and the economics of scale would be discussed here. The difference between two methods depends on the packaging materials and equipments. On the other hand, the variant in wafer cost is also taken into consideration.[39]

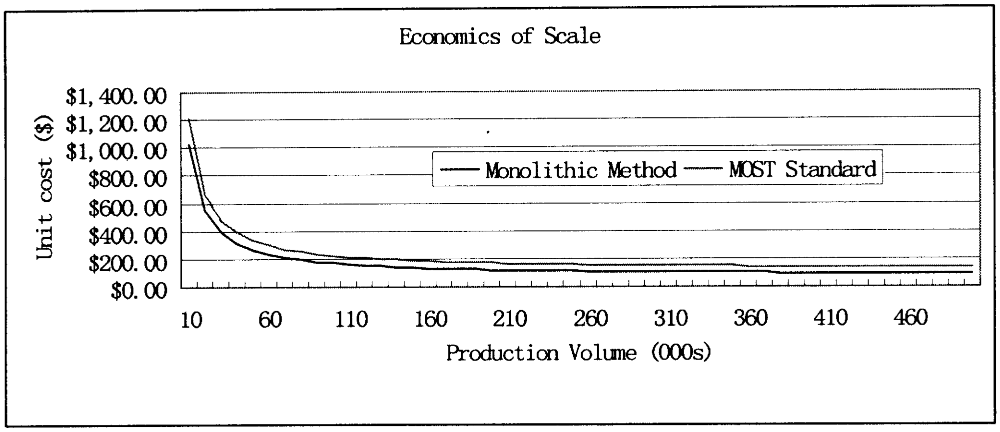


Fig.6.2 Economics of Scale of MOST standard and monolithic method.

The graph shows that the MOST standard is more expensive than the monolithic method. This is due to the extra money spent on equipment and materials for difficult packaging process. And when the annual production volume reaches 200,000 units, the economics of scale is achieved and the unit cost for Monolithic and MOST standard are $121.64, $170.13 separately. Usually, the yield of monolithic method should be lower than that of MOST, which is discrete process, because of the difficulty in process. However, the calculation set the yield of monolithic technology is 7% while MOST is 10%. The value maybe a little bit different to the real number. Therefore, the yield dependence is conducted here.[40]

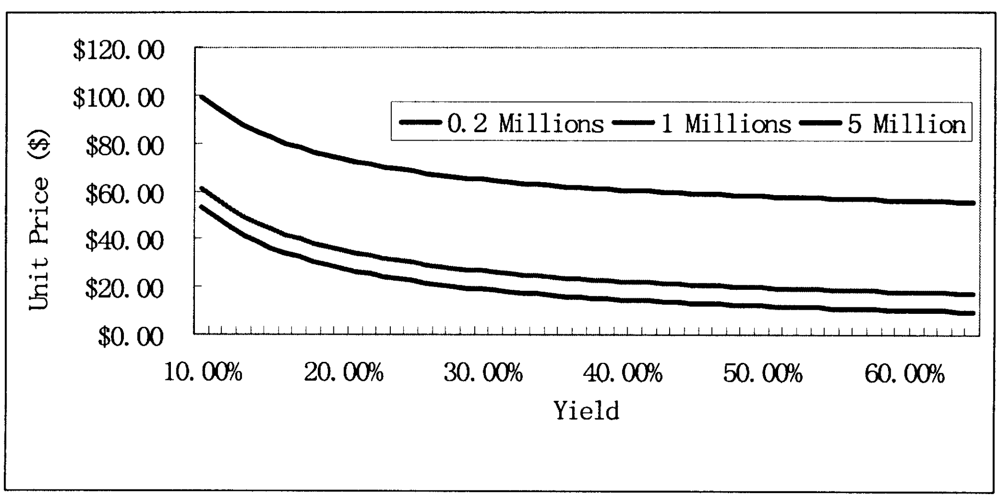


Fig. 6.3 Yield Dependence of monolithic method

From the curve, the higher yield can decrease the unit price dramatically and the unit price would reach $10 only when the yield achieves 64% and the production volume reaches 5 million. Although the production volume can reach that quantity which would be analyzed below, it takes a long time to get the higher yield.

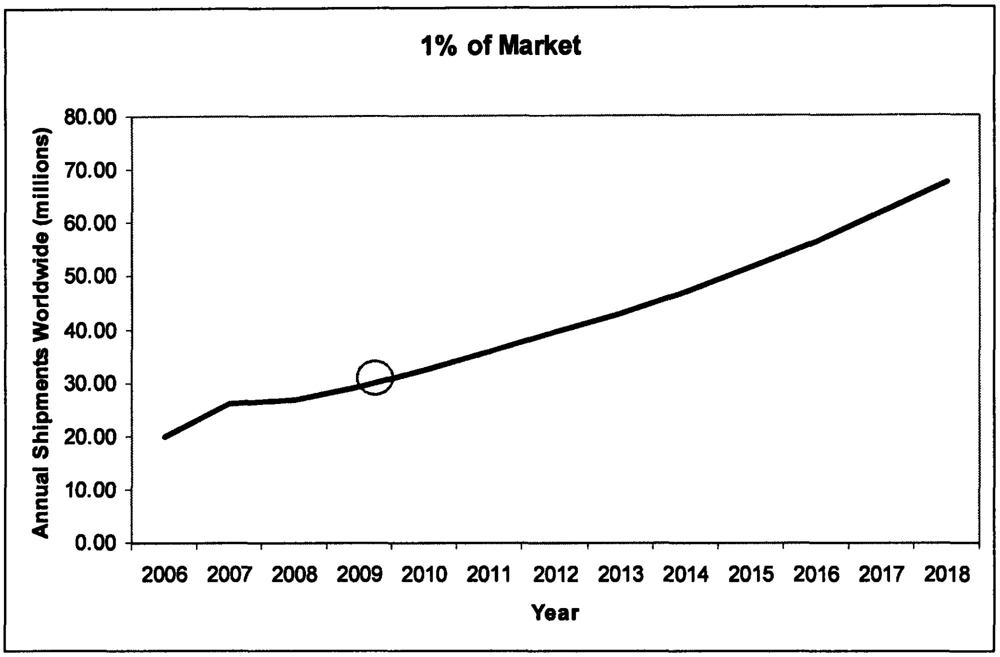


Fig. 6.4 Worldwide market for USB enabled devices.

The above figure shows the prediction from instat. And with the novel technology, such as wireless USB, this market is expected to be even larger than this. From the graph, in 2010, 5% of the worldwide annual shipments would exceed 150 million, which means the bottom line of economic of scale. Furthermore, according to the report from instate, it takes five year for USB 2.0 to occupy 50 percent of the total USB market share. And the second year after the production of USB 2.0, the market share has already exceeded 5% as showed below.

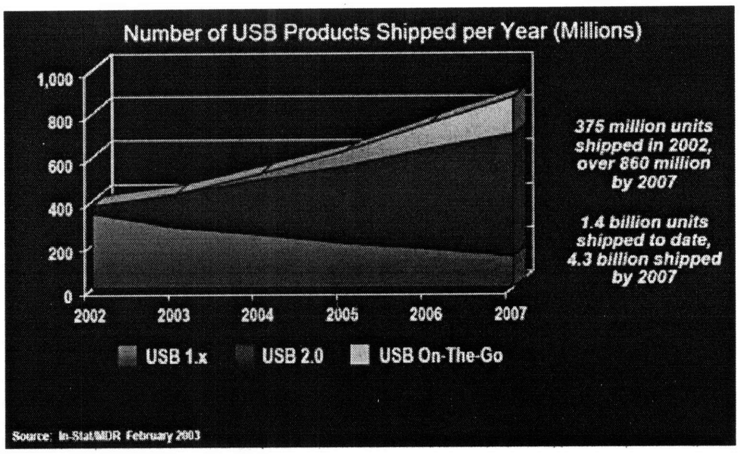


Fig. 6.5 Market penetration from USB 1.1 to USB 2.0.

With the general trend in information technology that the renovation happens faster and faster, it is reasonable to foresee a fast penetration speed for optical based USB.[11] Hence, the high production volume of optical based USB devices can be achieved within five year and the advanced technology should be applied for high yield to reduce the cost.

## 6.3 Business Plan

Currently, the price for 4 Gb memory USB and 8Gb memory USB, which are all electronic based products, would be sold at $60 and $120 each. Excluding the cost for storage component, it is reasonable to assume the price of optical based USB port, which can function at 10 Gb/s, to be $30 each. However, this price is relatively low for current technology, which can only get less than 10% yield. On the other hand, based on the analysis above, in the near term, the economics of scale would only reach when PCI express 3 is released and adopting optical interface. It can be expected that the yield at that time would reach larger than 10%.

Although the price is still low compare to the cost and is not suitable for business recently, the opportunity for optical connection would be promising within 5 years. If the yield is higher than 20% and the annual production volume can reach 5 million, which is much less than 1 % of the worldwide market share. Then it is benefit to conduct the business plan.

| Year | Fixed | Variable | Revenue | Profit | PV |
|---|---|---|---|---|---|
| 2011 | $95.40 | $129.40 | $150.00 | -$74.80 | -$74.80 |
| 2012 | | $129.40 | $150.00 | $20.60 | $19.62 |
| 2013 | | $129.40 | $150.00 | $20.60 | $18.68 |
| 2014 | | $129.40 | $150.00 | $20.60 | $17.80 |
| 2015 | | $129.40 | $150.00 | $20.60 | $16.95 |
| 2016 | | $129.40 | $150.00 | $20.60 | $16.14 |
| 2017 | | $129.40 | $150.00 | $20.60 | $15.37 |
| 2018 | | $129.40 | $150.00 | $20.60 | $14.64 |
| 2019 | | $129.40 | $150.00 | $20.60 | $13.94 |
| 2020 | | $129.40 | $150.00 | $20.60 | $13.28 |
| | | | | NPV | $71.62 |

Table 6.2 Business Plan for Monolithic Technology

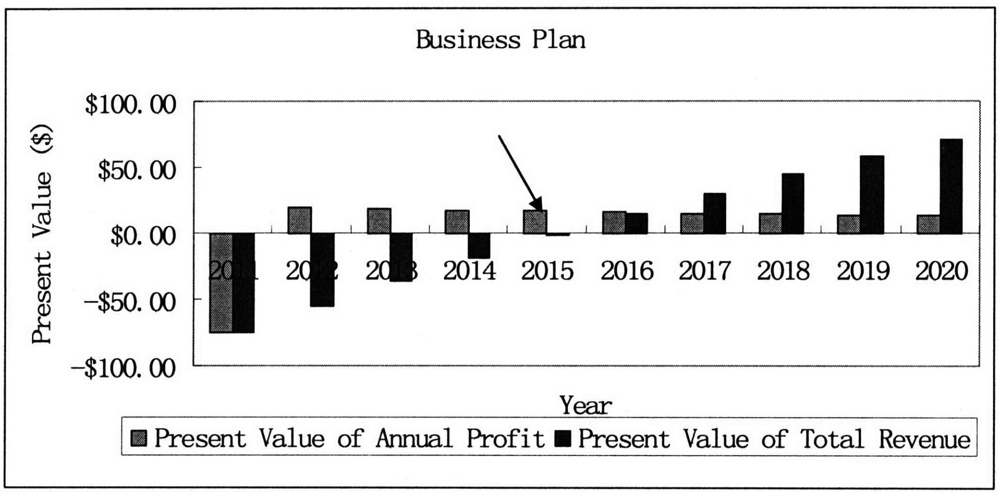


Fig. 6.6 NPV calculation for proposed business plan of monolithic technology.

The calculation assumes that profit for unit product is less than $3, which is sold at $30. The breakeven would happen at the fifth year and the total. The total NPV is $71.62 M. With the higher processing speed around 10 GHz, larger revenue can be expected for higher selling price. Thus, the revenue would be much larger.

The same analysis has been done on MOST standards. As the discussion above, the cost would be much higher than Monolithic method and it would be profitable only if the selling price can be around $120 per unit. Setting the price at $120 and production volume as 5 million as well, the results are showed below.

| Year | Fixed | Variable | Revenue | Profit | PV |
|---|---|---|---|---|---|
| 2011 | $110.40 | $574.65 | $600.00 | -$85.05 | -$85.05 |
| 2012 | | $574.65 | $600.00 | $25.35 | $24.14 |
| 2013 | | $574.65 | $600.00 | $25.35 | $22.99 |
| 2014 | | $574.65 | $600.00 | $25.35 | $21.90 |
| 2015 | | $574.65 | $600.00 | $25.35 | $20.86 |
| 2016 | | $574.65 | $600.00 | $25.35 | $19.86 |
| 2017 | | $574.65 | $600.00 | $25.35 | $18.92 |
| 2018 | | $574.65 | $600.00 | $25.35 | $18.02 |
| 2019 | | $574.65 | $600.00 | $25.35 | $17.16 |
| 2020 | | $574.65 | $600.00 | $25.35 | $16.34 |
| | | | | NPV | $95.13 |

Table 6.3 Table 6.1 Business Plan for MOST standard

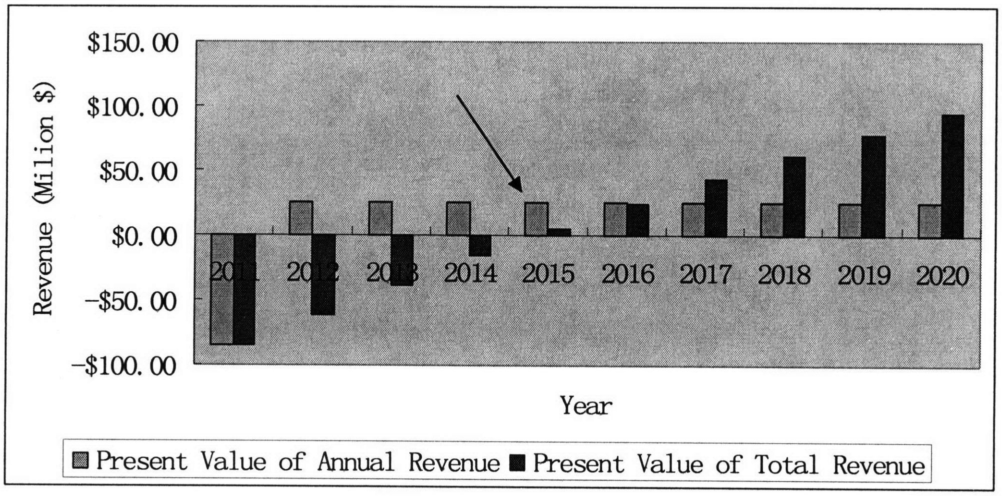


Fig. 6.7 NPV calculation for proposed business plan of MOST standard.

Similarly, the breakeven point is at the fifth year and the total NPV would be $95.13 million. However, the selling price is $120 per unit.

## 6.4 Discussion

According to the analysis above, the proposed business would aim at year 2011, which is one year after the production of PCI express 3 standard. With the back plane standard integrating optical port, the economic of scale would be achieved easily for optical based USB and a big profit can be made.

# Chapter Seven: Conclusion

Three markets, LAN, SAN and short cable have been discussed. The LAN market would be mature soon while the SAN should go to standardization based on Active Cable technology. For the short cable range, it is the right period for usage of optics as the cutting edge of electronic devices is reached in this range. However, there is no high bandwidth demanding for 5GHz-6GHz in this distance. In order to get the economic of scale, the producer should wait for the optical based standard released by PCI express 3. Another key issue would be the yield problem. Since the monolithic technologies have been just reported, the higher yield can be expected with improvements in a lot of aspects. When the economic of scale and high yield have been achieved, it can make big profit if only aiming at USB market. The following is the expected timeline for optical connection in short cable area carried out by this work.

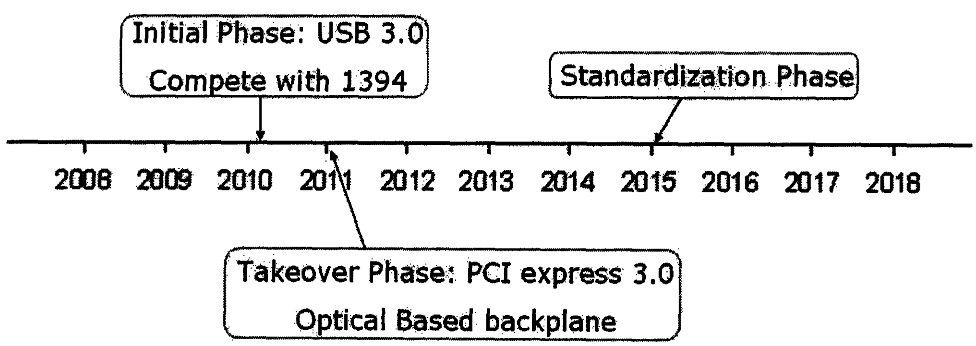


Fig. 7.1 Proposed Timeline for Optical Connection in Short Cable Area.

# Appendix I: Bandwidth Discussion of Coaxial Cable

For ultra high frequency function, coaxial is the best way for copper interconnection. Compare to two-wire open line, twin lead and twisted pair, coaxial cable has lower radiation loss while smaller size than shield pair. The structure and principle of coaxial cable can be illustrated as below.

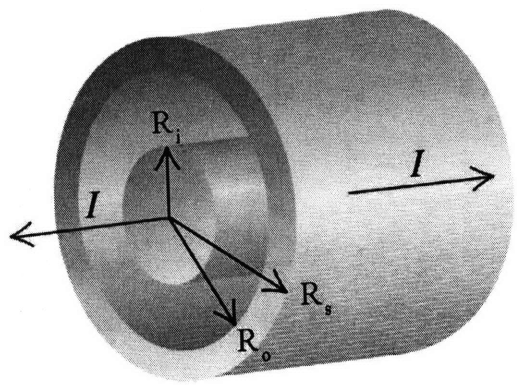


Fig. I1 Basic structure of coaxial cable.

The core conductor is set the transmission media for electronic signal while the outer conductor is just used to minimize radiation loss. In order to shield the electromagnetic wave, the current with same magnitude and opposite transmission direction should flow on the outer conductor, which can be modeled by two transmission line theory as well.[41]

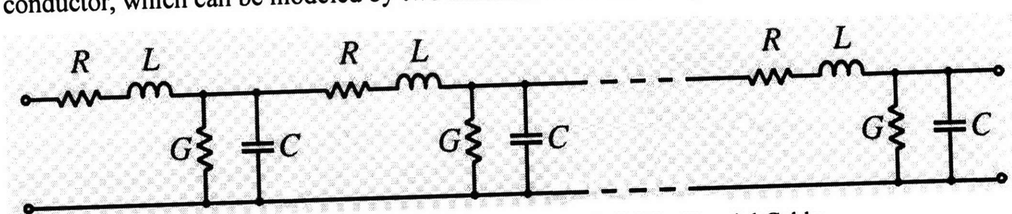


Fig. I2 Distributed Transmission Line Model for Coaxial Cable

Based on the distributed RLC model with frequency dependence, the uncoupled second-order differential equations are showed below:

$$\frac{d^2V}{dx^2} - k^2(s)V = 0$$

$$\frac{d^2 I}{dx^2} - k^2(s) I = 0$$

$V$ and $I$ are the expression for voltage and current on the coaxial cable while $k(s)$ denotes for the propagation function in frequency domain.

$$k(s) = \sqrt{(R + sL)(G + sC)}$$

Basically, $k(s)$ has both real and imaginary part, representing loss and dispersion separately. The general solution of the line equation can be written in the so-called 'traveling wave' form:

$$V(x,s) = V^+(s)\exp(-k(s)x) + V^-(s)\exp(k(s)x)$$

$$I(x,s) = I^+(s)\exp(-k(s)x) + I^-(s)\exp(k(s)x) = \frac{1}{Z_c}\left[V^+(s)\exp(-k(s)x) - V^-(s)\exp(k(s)x)\right]$$

$Z_c$ is the impedance. In time domain, it can be showed as:

$$Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

where R, L, G and C represent the resistance of conductor, inductance for conductor, conductance of dielectric insulator and the capacitance, all of which should consider the frequency effect. In coaxial cable, they can be calculated as following.

$$R = \frac{1}{2\pi}\sqrt{\frac{\omega \mu_0 \mu_r \rho}{2}}\left(\frac{1}{R_i} + \frac{1}{R_o}\right)$$

$$C = \frac{2\pi \varepsilon_0 \varepsilon_r}{\ln(R_o / R_i)}$$

$$L = \frac{\mu_0 \mu_r}{2\pi} \ln(R_o / R_i)$$

$$G = \frac{2\pi\sigma}{\ln(R_o / R_i)}$$

$\omega$ is the angle frequency for the electronic signal, $\mu_r$ is the permeability of the dielectric and $\varepsilon_r$ is its permittivity. $\rho$ is the resistively of the inner conductor and $\sigma$ is the conductivity in the dielectric.

In order to work normally, the load on the transmission line should match that on the transmission line. Usually, at high enough frequency,

$$Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \to \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{\frac{L}{C}},$$

which is a constant. Hence, the boundary frequency to let $Z_c$ almost equal to constant defines the lower cutoff frequency.

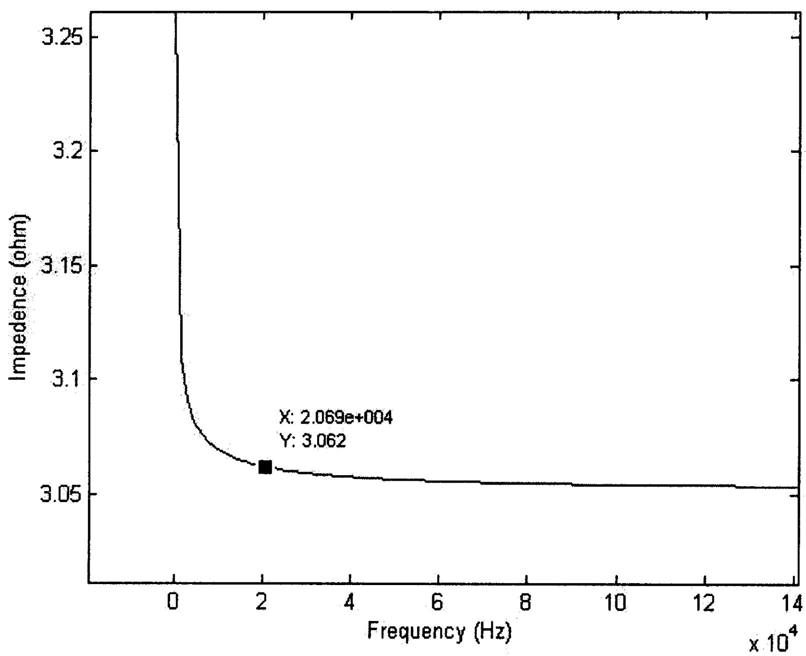


Fig. I3 Lower Cutoff Frequency of Coaxial Cable due to Impedances Mismatch

The above picture shows the frequency dependence of impedance. The value saturates above certain frequency and this is the work region for transmission line.

On the other hand, the loss on transmission line by coaxial wire increases while the frequency increases. As mentioned before, the real part of the propagation function would describe the loss on the transmission.

$$k(s) = \sqrt{(R + j\omega L)(G + j\omega C)} \sim \omega$$

The magnitude of $k(s)$ is proportional to $\omega$, which shows the large loss when working on high modulation frequency. If consider a sinusoidal wave with radian frequency $\omega$, the result in time domain can be obtained by replacing parameter s with $j\omega$. Finally, voltage and current in time domain can be calculated and the power attenuation is obtained as following:

$$\frac{P_o}{P_i} = \exp(-2\gamma z),$$

where $\gamma$ is the real part of propagation function and is called attenuation factor. If consider the transmission for 10 meters, 3dB would equal to $\gamma = 1/20 = 0.05$ for ideal case. This would define the upper cutoff frequency which is usually illustrated as below:

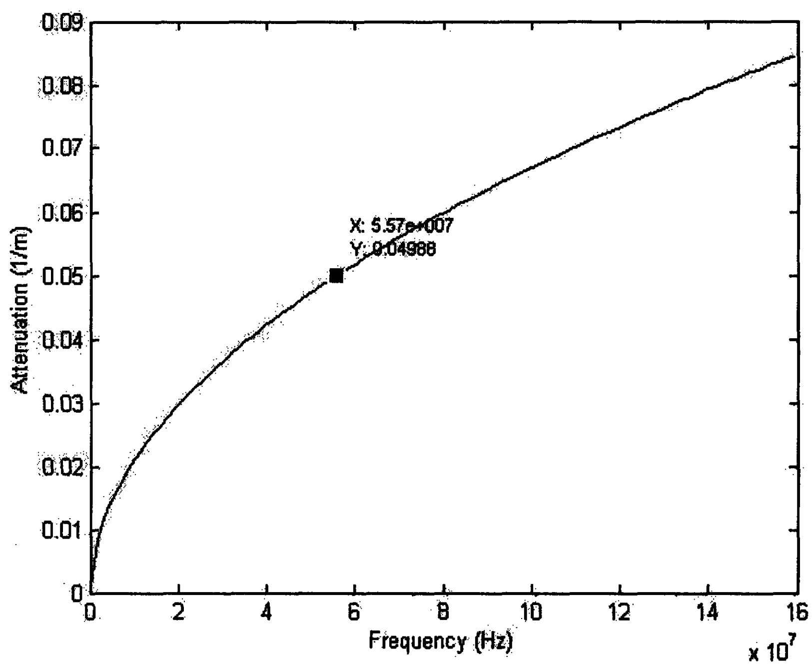


Fig. 14 Upper Cutoff Frequency for Coaxial Cable due to Attenuation

The attenuation factor increases monotonously with frequency. With lower requirement on transmission distance, attenuation can reach larger value. Thus, the upper cutoff frequency is defined in this way and the bandwidth is just the range between the lower and upper cutoff frequency.

However, the real case cannot be the ideal one and the attenuation is modified as following.

$$\frac{P_o}{P_i} = A\exp(-2\gamma z - Bz)$$

where A denotes for factor of the matching loss and B for unit transmission loss on the cable. Based on the parameters of current products, matching loss is set as 1dB and transmission loss is set as 1dB/m as well. Hence, both A and B are calculated in that way.

For the simulation here, copper is chosen as the conductor and dielectric material is adopted polyethylene. All constants in the simulation are written in the following table.

| Constant | Value |
|---|---|
| Resistively of Copper | $16.78\times10^{-9} n\Omega\cdot m$ |
| Conductivity of Polyethylene | $10^{-14}\Omega^{-1}m^{-1}$ |
| Relative Permeability of Polyethylene | 1 |
| Relative Permittivity of Polyethylene | 2.26 |

Table I1 Constants Used in Calculation

At first, relationship of bandwidth with dimension of the cable is calculated and the transmission distance is set as 3.6 meters first. The following graph shows the general dependence between them.

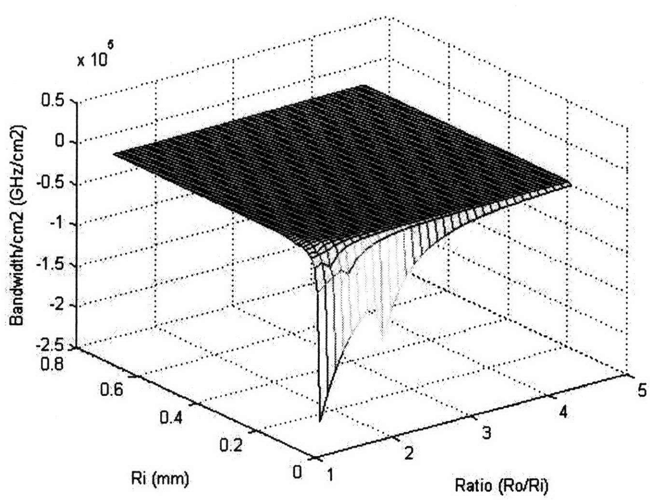


Fig. I5 Dimension Dependence on Bandwidth/cm$^2$ for Coaxial Cable

The x-axis and y-axis shows the ration between the ratio of two conductors while the z-axis is the bandwidth of the transmission line. From the graph, it can be concluded that the bandwidth saturates when radius of inner conductor becomes large. This can be explained by skin effect. As the frequency becomes large, the current would travel only on the surface of the cable other than the whole line. Hence, no matter how large the radius of cable is, the effective transmission region is fixed.

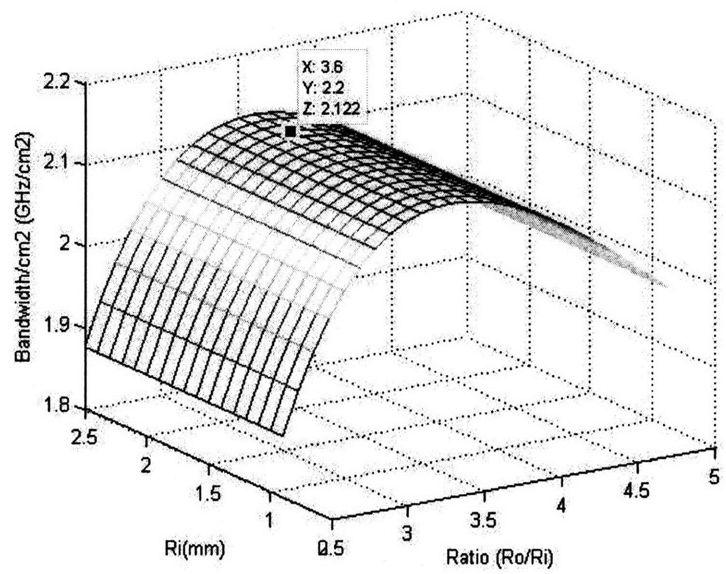


Fig. I6 Detailed Dimension Dependence on Bandwidth/cm$^2$ for Coaxial Cable

The above picture is the zoom in calculation of the dimension dependence on bandwidth and the range of dimension is based on the current products. It shows that the bandwidth has a maximum value with increasing of the radius of outer conductor. The reason can be illustrated as following. If the radius of the dielectric material is too small, the capacitance between inner and outer conductor would have a big effect on the attenuation. On the other hand, the shielding function of the outer conductor is not effective when the dielectric is very thick.

Furthermore, the dimension dependence on the bandwidth would not be affected by the transmission distance, which means the maximum value would appear at certain Ri and Ro. Therefore, the simulation later is conducted according to the best dimensions, which are 2.2

mm and 3.6 here.

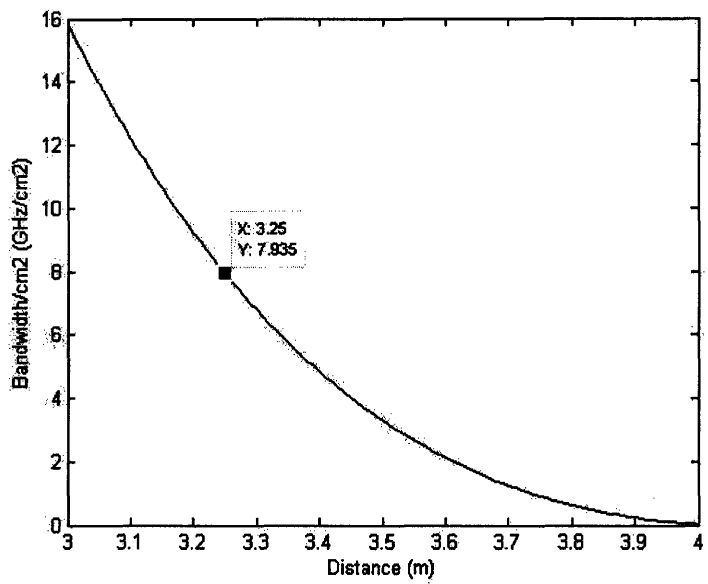


Fig. I7 Bandwidth versus Distance.

The above curve shows that the bandwidth decrease significant when transmission distance increase. Furthermore, when the distance is larger than 3,25 meters, the coaxial cable cannot function above 8GHz, which would be the penetration bandwidth discussed in the work.

# Appendix II: Bandwidth of Optical Fiber

Both attenuation and phase matching of optical fiber would be conducted as in the coaxial cable case.

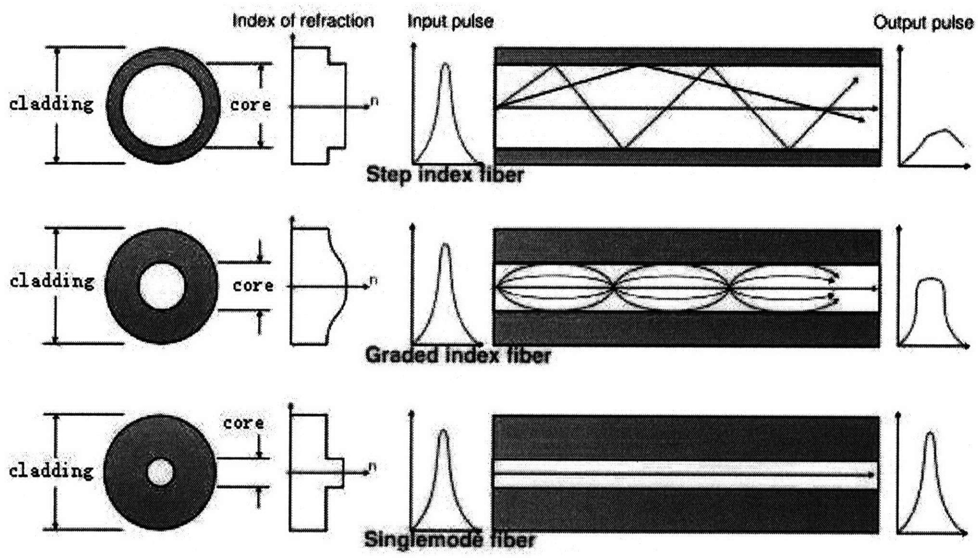


Fig. II1 General Profile for Optical Fiber

Usually, the optical fiber consists with the inner core and the cladding layer. The mechanism for transmission is due to total reflection. Depending on the profile of optical fiber, different model is traveling in the fiber. The model function can be calculated by

$$\nabla^2 \vec{E} + \nabla\left(\frac{1}{n^2}\nabla n^2 \cdot \vec{E}\right) - \varepsilon_0 \mu_0 n^2 \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

$$\nabla^2 \vec{H} + \frac{1}{n^2}\nabla n^2 \times \left(\nabla \times \vec{H}\right) - \varepsilon_0 \mu_0 n^2 \frac{\partial^2 \vec{H}}{\partial t^2} = 0$$

Then the loss and dispersion of each model can be obtained and compared.

In order to use the optical in long distance transmission, a lot of work has been done to reduce the loss on optical fiber. Currently, the optical fiber can already be used in long distance transmission, which shows the ultra low attenuation on the fiber.[42]

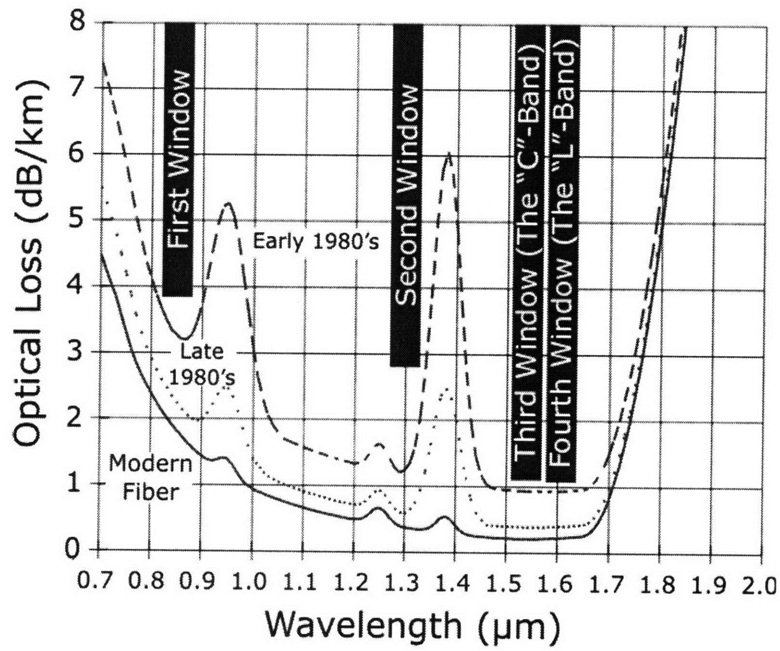


Fig. II2 Attenuation on Optical Fiber

The above graph shows the improvement process of optical fiber. As the unit used here is dB/km, which means the loss in 1-10meters can be neglected. Hence, the only limitation lies on the phase matching part.[34]

Therefore, the key consideration of optical fiber is the dispersion. There are two kinds of dispersion, material dispersion and index dispersion. The material dispersion is caused by the different refractive index to different wavelength on the same fiber while the index dispersion is caused by the wavelength it self. On the other hand, they disperse the wave in different ways, in specifically, opposite ways. The material dispersion usually causes the longer wavelength part to travel faster than the shorter ones while the index dispersion leads to the opposite effect. Hence, they compensate to each other and result in even smaller dispersion. For normal silicon step index fiber, they cancel each other in the region around 1.3 micrometers.

The details of index fiber is calculated and discussed below. The parameters are listed in the table below.

| Parameter | Value |
|---|---|
| Refractive index of inner core | 1.4508 |
| Refractive index of cladding | 1.4469 |
| Diameter of inner core | 4.1 μm |

Table II1 Parameters for index fiber discussed below.

According to the analysis, the material dispersion and index dispersion is calculated using following equation.

$$D_m = \frac{\Delta\tau}{L\Delta\lambda_0} = -\frac{1}{\lambda_0 c}\left(\lambda_0^2 \frac{d^2 n}{d\lambda_0^2}\right)\times 10^9\ ps/km\cdot nm$$

$$D_i = -\frac{n_2\Delta}{3\lambda_0}\left(V\frac{d^2(bV)}{dV^2}\right)\times 10^7\ ps/km\cdot nm$$

$$D_t = D_m + D_i$$

Where V is normalized waveguide parameter and b is normalized propagation constant.

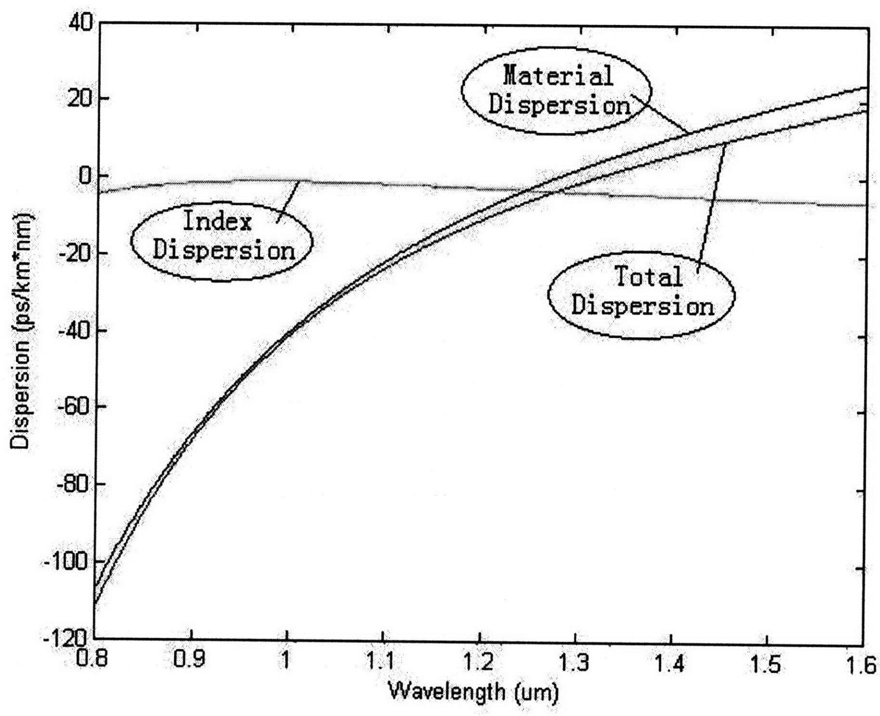


Fig. II3 Dispersion on Optical Fiber

The above picture shows three kinds of dispersion on the curve and the frequency limitation is just the inverse of dispersion, which is showed in Chapter 5. Here shows the bandwidth for this fiber in the commercialized transmission band.

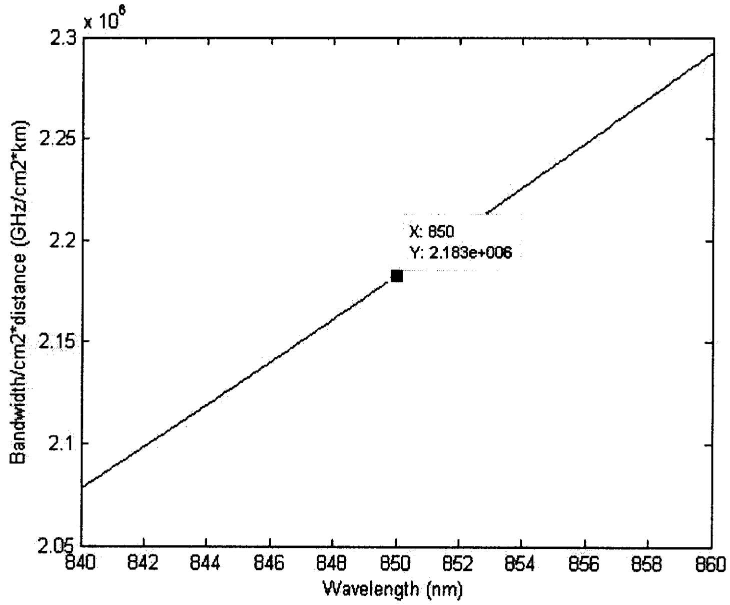


Fig. II4 Bandwidth for 850nm window.

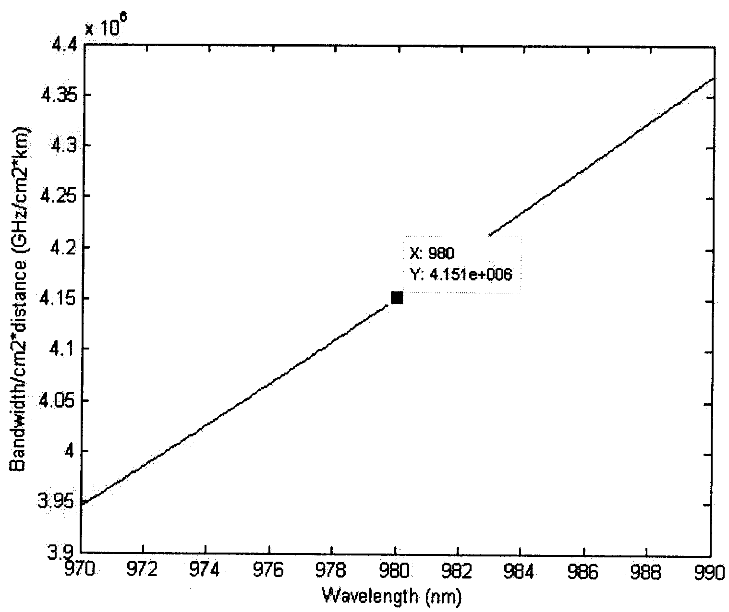


Fig. II5 Bandwidth of 980nm window.

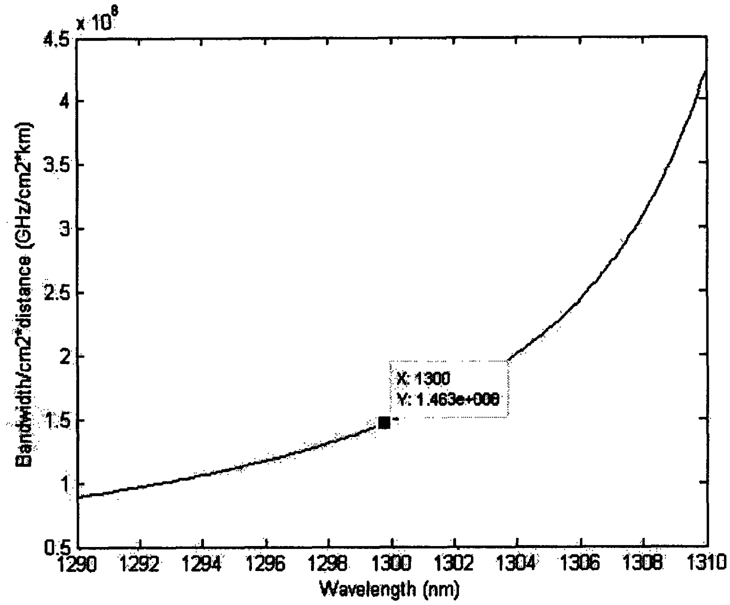


Fig. II6 Bandwidth of 1300nm window.

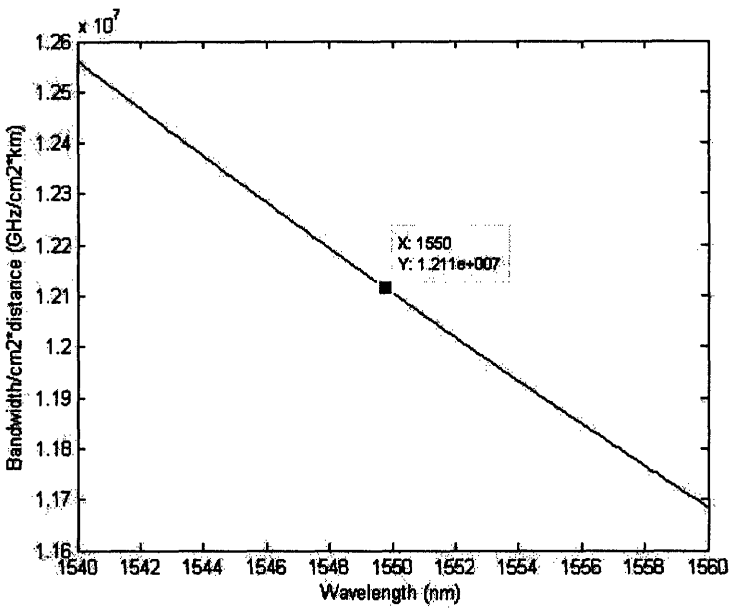


Fig. II7 Bandwidth of 1550nm window.

It can be concluded that the bandwidth can easily reach $10^6$ GHz/cm$^2$*km.

# Appendix III: Cost Modeling Analysis for Optical Based USB Product

The detail cost modeling is illustrated below.

| Production Volume | mono | MOST | Production Voolume | mono | MOST |
|---|---|---|---|---|---|
| 10000 | $1,027.94 | $1,218.93 | 490000 | $93.41 | $137.46 |
| 20000 | $550.94 | $666.93 | 500000 | $93.02 | $137.01 |
| 30000 | $391.94 | $482.93 | 600000 | $89.84 | $133.33 |
| 40000 | $312.44 | $390.93 | 700000 | $87.57 | $130.70 |
| 50000 | $264.74 | $335.73 | 800000 | $85.87 | $128.73 |
| 60000 | $232.94 | $298.93 | 900000 | $84.54 | $127.20 |
| 70000 | $210.23 | $272.64 | 1000000 | $83.48 | $125.97 |
| 80000 | $193.19 | $252.93 | 1100000 | $82.62 | $124.97 |
| 90000 | $179.94 | $237.60 | 1200000 | $81.89 | $124.13 |
| 100000 | $169.34 | $225.33 | 1300000 | $81.28 | $123.42 |
| 110000 | $160.67 | $215.29 | 1400000 | $80.76 | $122.82 |
| 120000 | $153.44 | $206.93 | 1500000 | $80.30 | $122.29 |
| 130000 | $147.33 | $199.85 | 1600000 | $79.91 | $121.83 |
| 140000 | $142.09 | $193.79 | 1700000 | $79.55 | $121.42 |
| 150000 | $137.54 | $188.53 | 1800000 | $79.24 | $121.06 |
| 160000 | $133.57 | $183.93 | 1900000 | $78.96 | $120.74 |
| 170000 | $130.06 | $179.87 | 2000000 | $78.71 | $120.45 |
| 180000 | $126.94 | $176.26 | 2100000 | $78.49 | $120.19 |
| 190000 | $124.15 | $173.04 | 2200000 | $78.28 | $119.95 |
| 200000 | $121.64 | $170.13 | 2300000 | $78.09 | $119.73 |
| 210000 | $119.37 | $167.50 | 2400000 | $77.92 | $119.53 |
| 220000 | $117.31 | $165.11 | 2500000 | $77.76 | $119.35 |
| 230000 | $115.42 | $162.93 | 2600000 | $77.61 | $119.18 |
| 240000 | $113.69 | $160.93 | 2700000 | $77.48 | $119.02 |
| 250000 | $112.10 | $159.09 | 2800000 | $77.35 | $118.87 |
| 260000 | $110.64 | $157.39 | 2900000 | $77.23 | $118.74 |
| 270000 | $109.28 | $155.82 | 3000000 | $77.12 | $118.61 |
| 280000 | $108.01 | $154.36 | 3100000 | $77.02 | $118.49 |
| 290000 | $106.84 | $153.00 | 3200000 | $76.92 | $118.38 |
| 300000 | $105.74 | $151.73 | 3300000 | $76.83 | $118.28 |
| 310000 | $104.72 | $150.54 | 3400000 | $76.75 | $118.18 |
| 320000 | $103.76 | $149.43 | 3500000 | $76.67 | $118.08 |
| 330000 | $102.85 | $148.38 | 3600000 | $76.59 | $118.00 |
| 340000 | $102.00 | $147.40 | 3700000 | $76.52 | $117.91 |

| | | | | | |
|---|---|---|---|---|---|
| **350000** | $101.20 | $146.47 | **3800000** | $76.45 | $117.84 |
| **360000** | $100.44 | $145.60 | **3900000** | $76.39 | $117.76 |
| **370000** | $99.73 | $144.77 | **4000000** | $76.33 | $117.69 |
| **380000** | $99.05 | $143.98 | **4100000** | $76.27 | $117.62 |
| **390000** | $98.40 | $143.24 | **4200000** | $76.21 | $117.56 |
| **400000** | $97.79 | $142.53 | **4300000** | $76.16 | $117.50 |
| **410000** | $97.21 | $141.86 | **4400000** | $76.11 | $117.44 |
| **420000** | $96.66 | $141.22 | **4500000** | $76.06 | $117.38 |
| **430000** | $96.13 | $140.60 | **4600000** | $76.02 | $117.33 |
| **440000** | $95.62 | $140.02 | **4700000** | $75.97 | $117.28 |
| **450000** | $95.14 | $139.46 | **4800000** | $75.93 | $117.23 |
| **460000** | $94.68 | $138.93 | **4900000** | $75.89 | $117.18 |
| **470000** | $94.24 | $138.42 | **5000000** | $75.85 | $117.14 |
| **480000** | $93.82 | $137.93 | **5100000** | $75.81 | $117.09 |

Table III1 Cost Modeling for monolithic technology and MOST standard

| | **Monolithic Technology** | | | **MOST Standard** | | |
|---|---|---|---|---|---|---|
| **Yield** | **0.2 Million** | **1 Million** | **5 Million** | **0.2 Million** | **1 Million** | **5 Million** |
| **1.00%** | $565.30 | $527.14 | $519.51 | $1,204.50 | $1,160.34 | $1,151.51 |
| **2.00%** | $306.50 | $268.34 | $260.71 | $629.85 | $585.69 | $576.86 |
| **3.00%** | $220.23 | $182.07 | $174.44 | $438.30 | $394.14 | $385.31 |
| **4.00%** | $177.10 | $138.94 | $131.31 | $342.53 | $298.37 | $289.53 |
| **5.00%** | $151.22 | $113.06 | $105.43 | $285.06 | $240.90 | $232.07 |
| **10.00%** | $99.46 | $61.30 | $53.67 | $170.13 | $125.97 | $117.14 |
| **15.00%** | $82.21 | $44.05 | $36.41 | $131.82 | $87.66 | $78.83 |
| **20.00%** | $73.58 | $35.42 | $27.79 | $112.67 | $68.51 | $59.67 |
| **25.00%** | $68.40 | $30.24 | $22.61 | $101.17 | $57.01 | $48.18 |
| **30.00%** | $64.95 | $26.79 | $19.16 | $93.51 | $49.35 | $40.52 |
| **35.00%** | $62.49 | $24.33 | $16.70 | $88.04 | $43.88 | $35.05 |
| **40.00%** | $60.64 | $22.48 | $14.85 | $83.93 | $39.77 | $30.94 |
| **45.00%** | $59.20 | $21.04 | $13.41 | $80.74 | $36.58 | $27.75 |
| **50.00%** | $58.05 | $19.89 | $12.26 | $78.19 | $34.03 | $25.19 |
| **55.00%** | $57.11 | $18.95 | $11.32 | $76.10 | $31.94 | $23.10 |
| **60.00%** | $56.33 | $18.17 | $10.53 | $74.36 | $30.20 | $21.36 |
| **65.00%** | $55.66 | $17.50 | $9.87 | $72.88 | $28.72 | $19.89 |
| **70.00%** | $55.09 | $16.93 | $9.30 | $71.62 | $27.46 | $18.63 |
| **75.00%** | $54.60 | $16.44 | $8.81 | $70.52 | $26.36 | $17.53 |
| **80.00%** | $54.17 | $16.01 | $8.38 | $69.57 | $25.41 | $16.57 |

Table III2 Yield Dependence for monolithic technology and MOST standard

## Reference


[1] 2007 ITRS Report, http://www.itrs.net/Links/2007ITRS/Home2007.htm

[2] 2005 CTR Report, http://mph-roadmap.mit.edu/index.php/ctr/ctr-i/transceivers

[3] A. F. Benner, M. Ignatowski, J. A. Kash, D. M. Kuchta, M. B. Ritter, 'Exploitation of optical interconnects in future server architectures', *IBM J. RES. & DEV. VOL. 49 NO. 4/5 JULY/SEPTEMBER* 2005

[4] Michael James Speerschneider, 'Technology and Policy Drivers for Standardization: Consequences for the Optical Components Industry', *MIT Thesis*

[5] Avago Technologies, http://www.avagotech.com/

[6] Finisar, http://www.finisar.com/home.php

[7] Addison Wesley Longman, Inc., http://www.pearsonhighered.com/

[8] 'Fundamentals of DWDM Technology', Chapter 2, CISCO

[9] PCI-SIG, http://www.pcisig.com/news_room/08_08_07/

[10] MOST, http://www.mostcooperation.com/home/index.html

[11] Instat, http://www.instat.com/

[12] B. Fallah-Azad et al., "Light emitting diodes on glass and silicon substrates fabricated using novel low temperature hydrogenation-assisted nano-crystallization of silicon thin films," in *Semiconductor Device Research Symposium, 2007 International*, 2007, 1-2, doi:10.1109/ISDRS.2007.4422517

[13] R. Nagarajan et al., "Gigabyte/s parallel fiber-optic links based on edge emitting laser diode arrays," *Lightwave Technology, Journal of* 16, no. 5 (1998): 778-787, doi:10.1109/50.669005

[14] N. Nishiyama et al., "Single-transverse mode and stable-polarization operation under high-speed modulation of InGaAs-GaAs vertical-cavity surface-emitting laser grown on GaAs (311) B substrate," *Photonics Technology Letters, IEEE* 10, no. 12 (1998): 1676-1678, doi:10.1109/68.730466

[15] A. Yi-Yan et al., "Grafted InGaAsP light emitting diodes on glass channel waveguides," *Electronics Letters* 28, no. 4 (1992): 341-342, doi:10.1049/el:19920213

[16] L.B. Aronson et al., "Transmitter optical subassembly for XFP applications," in *Electronic Components and Technology Conference, 2005. Proceedings. 55th*, 2005, 1058-1062 Vol. 1, doi:10.1109/ECTC.2005.1441402

[17] Sung Hwan Hwang, Jung Woon Lim, and Byung Sup Rho, "120 Gb/s-level VCSEL array optical subassembly using passive alignment technique," in *Electronic Components and Technology Conference, 2008. ECTC 2008. 58th*, 2008, 1620-1624, doi:10.1109/ECTC.2008.4550193

[18] J.K. So et al., "Experimental Study on 100GHz Two-Step LIGA-based Backward Wave Devices," in *Vacuum Electronics Conference, 2007. IVEC '07. IEEE International*, 2007, 1-2, doi:10.1109/IVELEC.2007.4283369

[19] J.C. Sun et al., "Ultraviolet electroluminescence from n-ZnO:Ga/p-ZnO:N homojunction device on sapphire substrate with p-type ZnO:N layer formed by annealing in N2O plasma ambient," *Chemical Physics Letters* 460, no. 4-6 (July 30, 2008): 548-551

[20] Hung-Fei Kuo, Sang-Yeon Cho, and N.M. Jokerst, "Heterogeneous integration of InP/InGaAsP MQW thin film edge emitting lasers and polymer waveguides," in *Electronic Components and Technology Conference, 2004. Proceedings. 54th*, vol. 2, 2004, 1537-1541 Vol.2, doi:10.1109/ECTC.2004.1320319

[21] K. Iga, "Surface-emitting laser-its birth and generation of new optoelectronics field," *Selected Topics in Quantum Electronics, IEEE Journal of* 6, no. 6 (2000): 1201-1215, doi:10.1109/2944.902168

[22] J.H. Choi et al., "Effects of Thermal-Via Structures on Thin-Film VCSELs for Fully Embedded Board-LevelOptical Interconnection System," *Selected Topics in Quantum Electronics, IEEE Journal of* 12, no. 5 (2006): 1060-1065, doi:10.1109/JSTQE.2006.881903

[23] "Monolithic CMOS-compatible AlGaInP visible LED arrays on silicon on

lattice-engineered substrates (SOLES)," February 1, 2007, http://www.iop.org.libproxy1.nus.edu.sg/EJ/abstract/0268-1242/22/2/006/

[24] Jifeng Liu et al., "High-performance, tensile-strained Ge p-i-n photodetectors on a Si platform," *Applied Physics Letters* 87, no. 10 (2005): 103501-3.

[25] M. Agethen et al., "InGaAs PIN detectors for frequencies above 100 GHz," in *Indium Phosphide and Related Materials Conference, 2002. IPRM. 14th*, 2002, 673-676, doi:10.1109/ICIPRM.2002.1014607

[26] M. T. Currie et al., "Controlling threading dislocation densities in Ge on Si using graded SiGe layers and chemical-mechanical polishing," *Applied Physics Letters* 72, no. 14 (April 6, 1998): 1718-1720

[27] Lorenzo Colace et al., "Ge on Si p-i-n photodiodes operating at 10 Gbit/s," *Applied Physics Letters* 88, no. 10 (March 6, 2006): 101111-3

[28] Douglas D. Cannon et al., "Germanium-rich silicon-germanium films epitaxially grown by ultrahigh vacuum chemical-vapor deposition directly on silicon substrates," *Applied Physics Letters* 91, no. 25 (December 17, 2007): 252111-3

[29] S. Abe et al., "Short wave SFF small form factor transceivers," in *Electronic Components and Technology Conference, 2001. Proceedings., 51st*, 2001, 30-34, doi:10.1109/ECTC.2001.927678.

[30] Dongchurl Kim et al., "Design and fabrication of a transmitter optical subassembly (TOSA) in 10-gb/s small-form-factor pluggable (XFP) transceiver," *Selected Topics in Quantum Electronics, IEEE Journal of* 12, no. 4 (2006): 776-782, doi:10.1109/JSTQE.2006.876184

[31] C. Baks et al., "Silicon optical bench for high-speed optical subassemblies [optical receiver]," in *Electronic Components and Technology Conference, 2004. Proceedings. 54th*, vol. 1, 2004, 1029-1035 Vol.1, doi:10.1109/ECTC.2004.1319466

[32] F. Ho et al., "Ultralow¿Cost Optical Transceiver Modules Based on Leadframe Plastic¿Package Technology," in *Electronic Components and Technology Conference, 2005. Proceedings. 55th*, 2005, 1032-1038, doi:10.1109/ECTC.2005.1441398

[33] A. Stohr, K. Kitayama, and T. Kuri, "Fiber-length extension in an optical 60-GHz transmission system using an EA-modulator with negative chirp," *Photonics Technology Letters, IEEE* 11, no. 6 (1999): 739-741, doi:10.1109/68.766803

[34] J.E. Schutt-Aine, "High-frequency characterization of twisted-pair cables," *Communications, IEEE Transactions on* 49, no. 4 (2001): 598-601, doi:10.1109/26.917765

[35] J. Chramiec and J.K. Piotrowski, "Universal formula for frequency-dependent coaxial open-end effect ," *Electronics Letters* 35, no. 17 (1999): 1474-1475, doi:10.1049/el:19990978

[36] M. Ravindran, "Cabled PCI express-a standard high-speed insterument interconnect," in *Autotestcon, 2007 IEEE*, 2007, 410-417, doi:10.1109/AUTEST.2007.4374248

[37] Jiuxing Liu et al., "Performance evaluation of InfiniBand with PCI Express," in *High Performance Interconnects, 2004. Proceedings. 12th Annual IEEE Symposium on*, 2004, 13-19, doi:10.1109/CONECT.2004.1375193

[38] Kamesh Chilukuri et al., "Monolithic CMOS-compatible AlGaInP visible LED arrays on silicon on lattice-engineered substrates (SOLES)," *Semiconductor Science and Technology* 22, no. 2 (2007): 29-34

[39] E.R.H. Fuchs et al., "Process-based cost modeling of photonics manufacture: the cost competitiveness of monolithic integration of a 1550-nm DFB laser and an electroabsorptive modulator on an InP platform," *Lightwave Technology, Journal of* 24, no. 8 (2006): 3175-3186, doi:10.1109/JLT.2006.875961

[40] V. Eramo, M. Listanti, and A. Germoni, "Cost Evaluation of Optical Packet Switches Equipped With Limited-Range and Full-Range Converters for Contention Resolution," *Lightwave Technology, Journal of* 26, no. 4 (2008): 390-407, doi:10.1109/JLT.2007.911102

[41] C. Gordon, T. Blazeck, and R. Mittra, "Time-domain simulation of multiconductor transmission lines with frequency-dependent losses," *Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on* 11, no. 11 (1992): 1372-1387, doi:10.1109/43.177401

[42] F. Matera and M. Settembre, "Exploitation of optical fibre capacity in long links,"

*Electronics Letters* 30, no. 10 (1994): 803-805
[43] David R. Goff., Fiber Optic Video Transmission