Two Channel SDM Communication System
Simultaneously Operating at 10Gb/s Using C-band Transceivers

By

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We the undersigned committee hereby approve the attached thesis, “Two channel SDM communication system simultaneously operating at 10Gb/s using C-band transceivers” by Han Wang.

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Abstract

Title: Two Channel SDM Communication System Simultaneously Operating at 10Gb/s Using C-band Transceivers

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Increasing the bandwidth of optical fiber communications to cope with high-speed network traffic is an important goal for the communications industry. Therefore, optical communication is growing at a very rapid pace, including the multiplexing technology. Spatial domain multiplexing (SDM), also known as Space division multiplexing, is a Multi-Input Multi-Output (MIMO) architecture that can increase the data carrying capacity of optical fibers by multiple folds. SDM allows multiple channels of same wavelength to be transmitted in parallel over standard multi-mode fibers, where each SDM channel follows a different helical trajectory while traversing the length of the fiber that lead to unique concentric donut-shaped rings at the output. These independent rings do not interfere with each other. The SDM system is similar to any optical communication system but requires two additional components, the spatial multiplexer and de-multiplexer also known as the Beam Combiner Module (BCM) and the Beam Separator Module (BSM) which are placed at the input and output ends of the system. Therefore, the design of BCM and BSM affect the performance of SDM systems. The successful operation of a two-channel SDM system for LAN applications, with associated BCM and BSM is presented. This two channel system operate at 10 Gb/s using C-band transceivers and allows spatial reuse of optical frequencies.
# Table of Contents

1. Introduction  
   1.1 Optical Communication Background  
   1.2 Optical Fiber Communication  
      1.2.1 Advantage of Optical Fiber Communication  
      1.2.2 Applications of Optical Fiber  
   1.3 Optical Fiber  
      1.3.1 Fiber Construction  
      1.3.2 Fiber Connector  
      1.3.3 Operating Principle of Optical Fiber  
      1.3.4 Light Propagation in Fibers  
      1.3.5 Numerical Aperture of Fiber  
      1.3.6 Attenuation and Dispersion  
   1.4 Optical Transmitter  
      1.4.1 Structure of Laser and LED  
      1.4.2 Modulation and Coding  
   1.5 Optical Receiver  
      1.5.1 PIN Photodiode and APD  
      1.5.2 Signal to Noise Ratio (SNR)  
      1.5.3 BER and Eye Diagram  
   1.6 Optical Transceiver module  
   1.7 Optical Power Budget  
      1.7.1 Mechanical Alignment  
      1.7.2 The Coupling of Source to Fiber  
2. Spatial Division Multiplexing Technology  
   2.1 Multiplexing Introduction  
      2.1.1 Time Division Multiplexing (TDM)  
      2.1.2 Code division Multiplexing (CDM)  
      2.1.3 Wavelength Division Multiplexing (WDM)  
      2.1.4 Polarization Division Multiplexing (PDM)  
   2.2 Spatial Division Multiplexing (SDM)  
   2.3 Orbital Angular Momentum Multiplexing (OAMM)  
3. Multiplexing of SDM  
   3.1 Introduction BCM  
      3.1.1 Lens and ABCD Matrix  
      3.1.2 Mode Field Diameter (MFD)  
   3.2 The BCM with Bare Fibers and Fiber Tubes  
   3.3 3D Printed BCM
4. De-Multiplexing of SDM
   4.1 CMOS  
   4.2 All Optical Lens De-Multiplexer  
   4.3 Beam Splitter De-Multiplexer  
   4.4 Prism De-Multiplexer  
   4.5 Mirror with Elliptical Hole De-Multiplexer  
5. Two Channel SDM Communication System in C-band
   5.1 Introduction  
   5.2 Simulation  
   5.3 Experiment setup  
   5.4 Link Analysis  
   5.5 System Testing and Analysis  
   5.6 Conclusion  
   5.7 Future Work
List of Figures

Figure 1.1 — Fundamental communication system ............................................. 1
Figure 1.2 — The block of a typical optical fiber communication system ........ 4
Figure 1.3 — The structure of optical fiber ....................................................... 8
Figure 1.4 — The structure of optical cable ..................................................... 8
Figure 1.5 — The layout of step index fiber .................................................... 9
Figure 1.6 — The layout of graded index fiber ............................................... 9
Figure 1.7 — Comparison with multimode fiber and single mode fiber .......... 10
Figure 1.8 — Comparison with multimode fiber and single mode fiber in 3D model ................................................................. 10
Figure 1.9 — Four types common optical fiber connector ............................. 11
Figure 1.10 — Refraction and reflection of light ray at a material boundary .... 12
Figure 1.11 — The meridional rays within the core of a step index fiber ......... 13
Figure 1.12 — The skew rays within the core of a step index fiber ............... 14
Figure 1.13 — The output pattern of skew ray projecting on a screen .......... 15
Figure 1.14 — Ray defining the numerical aperture ..................................... 16
Figure 1.15 — Attenuation of light propagation is affected by Rayleigh scattering .......................................................................................... 17
Figure 1.16 — Optical fiber attenuation curve with wavelength and optical fiber spectrum windows ........................................................... 18
Figure 1.17 — Intermodal dispersion in multimode fiber ............................... 20
Figure 1.18 — Two modulation approaches: Direct modulation & Indirect modulation ................................................................................. 22
Figure 1.19 — The block diagram of optical receiver ..................................... 22
Figure 1.20 — The layout of a pin photodiode circuit with an applied reverse bias ......................................................................................... 24
Figure 1.21 — The relation between BER versus Q factor .......................... 26
Figure 1.22 — Eight types of bit pattern (000, 001, 010, 011, 100, 101, 110, 111) are superimposed together to obtain an ideal eye diagram .......... 26
Figure 1.23 — The eye diagram of 10 Gbit/s XFP Transceiver formed by digital communication analyzer (DCA) ................................................. 28
Figure 1.24 — The 10 Gbps TXFP and 100 Gbps CWDM4 QSFP ............... 29
Figure 1.25 — Four type of mechanical misalignment and non-ideal situations that can occur between two joint fibers ........................................ 30
Figure 1.26 — The coupling loss of light source .......................................... 32
Figure 2.1 — Main Multiplexing technologies in optical fiber communication system ...................................................................................... 35
Figure 2.2 — The block diagram of time division multiplexing .................. 36
Figure 2.3 — The basic block diagram of wavelength division multiplexing .... 37
Figure 2.4 — The block diagram of SDM system .........................................................39
Figure 2.5 — Different combination of three channels SDM output profile by experiment ...........................................................40
Figure 2.6 — Different combination of three channels SDM output profile by Zemax simulation ........................................................41
Figure 2.7 — Gaussian beam wavefront ........................................................................42
Figure 2.8 — Intensity distribution and waveform of a Laguerre-Gaussian beam with \( l = 1 \) .......................................................................................44
Figure 2.9 — LG based 3 Channel SDM model .................................................................44
Figure 2.10 — Presentation of \( l = 0 \) (a), \( l = 1 \) (b), \( l = 2 \) (c), and \( l = 3 \) (d) for LG modes ........................................................................46
Figure 2.11 — A circular Photodetector divided into eight parts to detect OAM beams ........................................................................47
Figure 3.1 — The principle of focusing and collimating of a convex lens ......................52
Figure 3.2 — Relationship between Numerical aperture and Acceptance angle. 
\( (NA=\sin \theta_A) \) ........................................................................................................52
Figure 3.3 — Optical ABCD Matrix : (a) Homogeneous medium with length \( d \) and (b) Thin lens with focal length \( f \) ..................................................................................53
Figure 3.4 — The mode field diameter (MFD) of singlemode fiber ..................................54
Figure 3.5 — The four channels BCM with bare fibers in SDM and its output profile ........................................................................55
Figure 3.6 — The 3D modeling of fiber tubes multiplexer for 4 channels SDM simulated by Zemax ..............................................................56
Figure 3.7 — Four channel output pattern and profile of SDM system using Zemax ..............................................................................56
Figure 3.8 — Numerical aperture of carrier fiber and input fibers placed at an angle ..................................................................................57
Figure 3.9 — A multiple channels multiplexer with fiber tubes for SDM system .................58
Figure 3.10 — A four channels SDM output pattern created by fiber tube based multiplexer ........................................................................59
Figure 3.11 — A 3D modeling of fiber tubes multiplexer using Zemax ........................59
Figure 3.12 — 3D printed multiplexer cube and 3D module for BCM .........................61
Figure 3.13 — The layout of two channels SDM system with 3D printed multiplexer ........................................................................62
Figure 3.14 — The 3D model of BCM in SolidWorks .....................................................63
Figure 3.15 — The 3D model of BCM in Zemax .............................................................64
Figure 3.16 — Two channel SDM output and intensity profile simulated by Zemax ..............................................................................64
Figure 3.17 — The 3D printed BCM with Plano convex lens for two channel SDM ........65
Figure 3.18 — The output pattern of two channels SDM guided by 3D printed BCM ........................................................................................................................................ 66
Figure 4.1 — N-well/P-substrate concentric CMOS .................................................................................................................................................. 70
Figure 4.2 — The cross section of N-well/P-substrate concentric CMOS ................................................. 70
Figure 4.3 — The concentric CMOS photo-detector array ................................................................. 71
Figure 4.4 — The bulk lens de-multiplexer for two channel SDM .......................................................... 73
Figure 4.5 — The multi-focal points lens de-multiplexer for two channels SDM .......................................................... 73
Figure 4.6 — Bevel-edged hollow fiber De-multiplexer of two ring SDM...... ........................................ 74
Figure 4.7 — The block diagram of beam splitter de-multiplexer for two channel SDM ...................... 75
Figure 4.8 — The BSM of beam splitter in Zemax ................................................................................ 75
Figure 4.9 — The block diagram of combination of prisms based de-multiplexer for four channel SDM ........................................................................................................................................ 76
Figure 4.10 — The output profile of four channels SDM as detected by a photodetector in Zemax .......................................................................................................................... 76
Figure 4.11— The prism decomposes the different wavelength of light................................. 76
Figure 4.12 — The architecture of the optical lens array and mirrors for SDM de-multiplexer ........................................................................................................................................ 76
Figure 4.13— The mirror with elliptical hole for SDM de-multiplexing................................. 79
Figure 4.14 — (a) The CAD layout of the mirror array and (b) a customized mirror based SDM de-multiplexer .................................................................................................................. 79
Figure 4.15— The output profile of a four channels SDM system and the intensity profile of the four rings in Zemax simulation ........................................ 80
Figure 5.1 — The block diagram of two channels SDM communication system ........................................................................................................................................ 84
Figure 5.2 — The BCM model of two SDM channels simulated in Zemax ................... 85
Figure 5.3 — The BSM model of two SDM channels simulated in Zemax ............. 86
Figure 5.4 — Two channels SDM communication system setup ...................................................... 90
Figure 5.5 — The relationship of launching angle and input power ............................... 92
Figure 5.6 — A stable mount for BCM ............................................................................................. 93
Figure 5.7 — Microscopic view of fiber and the ball lens produced using electrical arc ........................................................................................................................................ 93
Figure 5.8 — Two channel BCM of SDM.................................................................................. 93
Figure 5.9 — The output profiles both center channel and outer channel after carrier fiber and collimating lens using 650nm laser ........................................ 94
Figure 5.10 — The top view of two channel BSM of SDM setup....................................... 94
Figure 5.11— The two visible rings separated by the mirror .............................................. 95
Figure 5.12 — Two channel SDM system evaluation process .......................................... 98
Figure 5.13 — The eye diagram and data rate of 11Gbps for center channel and outer channel for a 5 meters long carrier fiber .............................................. 100
Figure 5.14 — The eye diagram and data rate of 5Gbps for center channel and outer channel for a 5 meters long carrier fiber ..............................102
Figure 5.15 — The eye diagram and data rate at 5Gbps for center and outer channels in a 60 meters long carrier fiber .........................103
Figure 5.16 — The eye diagram and data rate at 11Gbps for center and outer channels in a 60 meters long carrier fiber ..........................105
Figure 5.17 — The eye diagram and data rate at 11Gbps for center and outer channels over a 150 meters long carrier fiber ......................107
Figure 5.18 — The bit pattern of center and outer channel restored by DCA ....108
Figure 5.19 — The eye diagram and data rate of 11Gbps for center and outer channels working at the same wavelength, 1561.83nm ..........112
Figure 5.20 — The eye diagram and data rate of 11Gbps for center and outer channels working at different wavelength (1552.52nm and 1536.22nm) ..................................................................................................................114
Figure 5.21 — The eye diagram and data rate of 11Gbps for center and outer channels both working at the same wavelength 1529.55nm ....115
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1.1</td>
<td>The compassion with electric cable and optical cable at attenuation and bandwidth</td>
<td>5</td>
</tr>
<tr>
<td>Table 1.2</td>
<td>Spectral band designations used in optical fiber communication</td>
<td>19</td>
</tr>
<tr>
<td>Table 1.3</td>
<td>The typical characteristic parameters of semiconductor diodes using for optical fiber communication</td>
<td>21</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>The parameters and output profile of each SDM channel using Zemax</td>
<td>65</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Experimental results for SDM channels</td>
<td>66</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Four channels SDM simulated results indicate no crosstalk or interference</td>
<td>81</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>The parameters of two channels in Zemax</td>
<td>86</td>
</tr>
<tr>
<td>Table 5.2</td>
<td>Combination of two SDM channels and output profiles</td>
<td>87</td>
</tr>
<tr>
<td>Table 5.3</td>
<td>The power budget of center and outer channel</td>
<td>88</td>
</tr>
<tr>
<td>Table 5.4</td>
<td>The testing of maximum length for two channels SDM</td>
<td>88</td>
</tr>
<tr>
<td>Table 5.5</td>
<td>Theoretical power budget of center channel with 60m carrier fiber</td>
<td>96</td>
</tr>
<tr>
<td>Table 5.6</td>
<td>Experimental power budget of center channel with 60m carrier fiber</td>
<td>96</td>
</tr>
<tr>
<td>Table 5.7</td>
<td>Theoretical power budget of outer channel with 60m carrier fiber</td>
<td>96</td>
</tr>
<tr>
<td>Table 5.8</td>
<td>Experimental power budget of outer channel with 60m carrier fiber</td>
<td>96</td>
</tr>
<tr>
<td>Table 5.9</td>
<td>Theoretical power budget of center channel with 150m link</td>
<td>97</td>
</tr>
<tr>
<td>Table 5.10</td>
<td>Experimental power budget of center channel with 150m link</td>
<td>97</td>
</tr>
<tr>
<td>Table 5.11</td>
<td>Theoretical power budget of outer channel with 150m link</td>
<td>97</td>
</tr>
<tr>
<td>Table 5.12</td>
<td>Experimental power budget of outer channel with 150m link</td>
<td>97</td>
</tr>
<tr>
<td>Table 5.13</td>
<td>The variable parameters in the testing system</td>
<td>99</td>
</tr>
<tr>
<td>Table 5.14</td>
<td>The parameters for two channels at 11Gbps in a 5 meters link</td>
<td>101</td>
</tr>
<tr>
<td>Table 5.15</td>
<td>The parameters of two channels with 5Gbps in a 5 meters link</td>
<td>103</td>
</tr>
<tr>
<td>Table 5.16</td>
<td>The parameters for two channels at 5Gbps over a 60 meters long link</td>
<td>104</td>
</tr>
<tr>
<td>Table 5.17</td>
<td>The parameters of two channels with 11Gbps in a 60 meters long link</td>
<td>106</td>
</tr>
<tr>
<td>Table 5.18</td>
<td>The parameters of two channels at 11Gbps in a 150 meters long link</td>
<td>107</td>
</tr>
<tr>
<td>Table 5.19</td>
<td>The output power for center and outer channels operating at C-band with 60 meters long carrier fiber</td>
<td>109</td>
</tr>
<tr>
<td>Table 5.20</td>
<td>The BER of center and outer channels operating at C-band with 60 meters long carrier fiber</td>
<td>109</td>
</tr>
</tbody>
</table>
Table 5.21 — Extinction Ratio for center and outer channels operating at C-band with 60 meters long carrier fiber.................................110
Table 5.22 — The output power of center and outer channels operating at C-band with 150 meters long carrier fiber.................................110
Table 5.23 — The BER for center and outer channels operating at C-band with 150 meters long carrier fiber...........................................111
Table 5.24 — Extinction Ratio for center and outer channels operating at C-band with 150 meters long carrier fiber.................................111
Table 5.25 — The parameters for two channels with 11Gbps in a 60 meters long link operating at the same wavelength (1561nm).....................113
Table 5.26 — The parameters of two channels with 11Gbps in a 60 meters long link at different wavelength (1552.52nm and 1536.22nm)............114
Table 5.27 — The parameters of two channels with 11Gbps over a 60 meters long link at the same wavelength (1529nm)............................116
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Dedication

I dedicate this thesis to my parents
Mr. Aimin Wang
And
Mrs. Hong Yuan
Chapter 1
Introduction

1.1 Optical Communication Background

The process of communication conveys information from one point to another. The information could be transmitted and received using different methods such as sign language, acoustics, symbols, optical and electrical signals etc. The block diagram of such a system is shown in figure 1.1. One of the older optical communications systems date back to 700 BC and was deployed in China. The locals established the Great Wall to defend against invaders. The Great Wall was connected by an array of sentry posts, which were situated within a couple of kilometers on high mountains. If the soldiers sitting on one of the sentry posts spotted an enemy, they would start burning moist wood, to generate plenty of smoke. According to some narrations, they would also add specific materials to the burning wood, to produce smoke of different colors. As the fire illuminated the sky and smoke started to rise, the adjacent posts would get the message, and the message would be relayed from one post to another, forming a long distance optical communications and signaling system.

![Figure 1.1: Fundamental communication system](image-url)
Another complete optical communications system dates back to the 1790s and is attributed to the French inventor, Claude Chappe, who designed the optical semaphore telegraph link. This system contains a semaphore line where a rod, with two wooden planks attached to it, was connected to a high tower with the help of chains. Different shapes of boards represented a different character. Hence information could be transmitted via various combinations of the boards. However, visibility was the biggest challenge to this system. Once the patterns became invisible, the transmission of information would be interrupted. This long range optical communication network was the precursor of modern communications [1].

In 1880, Alexander Graham Bell patented the optical telephone system at the Bell Laboratory [2]. Similarly the photophone was also a telecommunications device that used to convey vocal messages via light. Under favorable conditions, acoustic messages modulated by vibration of light pulse could transmit over 800 meters and communicate well. In the 1920s, a British engineer, John L. Baird, and an American engineer, Clarence W. Hansel, reported the innovation of optical communication using the transparent rods or pipes to transmit codes and images. In 1954, Abraham Van Heel who worked in a Dutch laboratory published a paper [3] about the bundles of cladding fibers. The fiber with cladding layer had attenuation of 1 dB/meter. It was acceptable for medical imaging applications, but it was a little too much loss for optical communication applications.

Theodore H. Maiman, an American physicist invented the first laser device using ruby as the medium of lasing in the 1960s [4]. LASER is an acronym of light amplification by stimulated emission of radiation. The laser has a very intense beam of light and high information carrying capacity, and it is a reliable choice as a transmitting source in the fiber. Advances in laser technology make commercial optical fiber communication system possible and affordable.
In 1964, American scientists Charles Kao and George Hockham published a paper, which theoretically and experimentally presented the feasibility of use of transparent glass for communication purposes. They also suggested that attenuation lower than 20 dB/km was possible through reduction of impurities in silica material. Cornur Maurer and his colleagues successfully produced a fiber waveguides with 17 dB/km attenuation at a wavelength of 0.633μm in 1970 [5]. Since then, more and more companies joined the competition to develop the optical communication technology leading to very rapid improvements and growth.

1.2 Optical Fiber Communication

As mentioned earlier, the optical fiber communication system uses light as signal and optical fibers as the transmission medium to transfer information from one place to another. In principle, the optical fiber communication system consists of the optical fiber, the transmitter typically consisting of a laser or an LED, and the receiver. On the transmitting side, electrical information is converted into optical, and then the light signal carrying the information is launched into the optical fiber. At the receiving end, a photodetector typically converts the optical signal back into the electrical. The optical transmitter generally uses semiconductor devices such as light-emitting diodes (LEDs) or laser sources and modulation circuitry. The core part of a receiver is typically a PIN photodetector, which converts light into electrical energy. Silica based optical fiber cables typically serve as the carrier or the medium for the optical fiber communication system. The optical fiber technology continues to grow rapidly to satisfy the demand for higher data rates for networking and long-haul communications [6]. Figure 1.2 shows the layout of a typical optical fiber communication system, which consists of three main components, the transmitter circuit that includes the light source, the optical fiber, and a receiver circuit that also contains the photodetector.
1.2.1 Advantages of Optical Fiber Communication

In the optical fiber communication system, the frequency of the light source is much higher than the frequency of the typical electrical signal. Furthermore, the attenuation of optical fiber as the communication medium is significantly lower than the coaxial cable. Therefore, compared to the coaxial cable or microwave systems, optical fiber communication offers many advantages. These include:

- **Wide bandwidth and big data capacity**

Optical fiber offers wider bandwidths than copper wires, so even a single line can transmit more information. The attenuation and bandwidth between the optical fiber and copper wire is presented in table 1.1. The copper wires are often used for lower data rate local area networks (LANs). The high-speed LANs (>100 Mbit/s), Metropolitan area networks (MANs) and Wide area networks (WANs) generally use optical fibers.
Table 1.1: The compassion with electric cable and optical cable at attenuation and bandwidth (Adopted from ref.7)

<table>
<thead>
<tr>
<th></th>
<th>Bandwidth</th>
<th>Attenuation (dB/km)</th>
<th>Transmission capacity (lines)</th>
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<tbody>
<tr>
<td>Symmetrical cable</td>
<td>4 kHz</td>
<td>2.06</td>
<td></td>
</tr>
<tr>
<td>Thin coaxial cable</td>
<td>30 MHz</td>
<td>28.7</td>
<td>960</td>
</tr>
<tr>
<td>Thick coaxial cable</td>
<td>60 MHz</td>
<td>18.77</td>
<td>1800</td>
</tr>
<tr>
<td>Multi-mode fiber</td>
<td>0.85 μm</td>
<td>200 ~ 1000 MHz</td>
<td>1920 (140 Mbit/s)</td>
</tr>
<tr>
<td></td>
<td>1.31 μm</td>
<td>&gt;1000 MHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td>Signal-mode fiber</td>
<td>1.31 μm</td>
<td>&gt;100 GHz</td>
<td>32000 (2.5 Gbit/s)</td>
</tr>
<tr>
<td></td>
<td>1.55 μm</td>
<td>10 ~ 100 GHz</td>
<td>491520 (40 Gbit/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

- **Low attenuation, long transmission distance**

The optical fiber has lower attenuation as compared to the copper wires so information can be transmitted to longer distance. As shown in the table 1.1, the loss of electric cable usually ranges between a few decibels to tens of decibels per kilometer. However, the optical fiber has a much lower loss, and a fiber operating at a wavelength of 1.55μm typically offers an attenuation of only 0.2 dB/km, or lower.

- **Small size and light weight**

The optical fiber has low weight and small dimensions. This is advantageous while installing the fiber in narrow underground applications. It is also useful in aircraft, satellites, and ship based applications.

- **Immunity to electromagnetic and radio frequency interference**

The optical fiber is made of electrically insulating quartz material, and the optical fiber communication line is immune to electromagnetic and radio frequency interference and lightning strikes. Therefore, the metal-free fiber cable is well suited...
near high voltage power lines as well as oil fields, coal mines and flammable chemical environments etc.

- **Information security**

The optical fiber does not radiate information in free space and it is not possible to remotely intercept information form the optical fiber without physically tapping into it. Any light leakage from the optical fiber is very weak and cannot be eavesdropped even in tight bending environments. Furthermore there are ways that could be employed to detect unauthorized tapping or bending of the fibers..

- **Saving metals, facilitating the rational use of resources**

Metals such as copper are typically used to manufacture of electrical cables and they have relatively limited reserves. On the contrary, the reserves of quartz (SiO2), the material needed to make the optical fiber is relatively abundant.

In short, the optical fiber is typically made of quartz glass and plastic. The quartz is an excellent electrical insulator. Hence it does not require any grounding or shielding and does not pose any electrical hazards. Furthermore, the optical signal cannot be tapped without physical access and it is immune to electromagnetic and radio frequency interferences.

### 1.2.2 Applications of Optical Fiber

Optical fiber cables are popular in various industries and applications. These include:

**Telecommunication**

Optical fiber cable is the medium of choice for telecommunication networks because of their high data capacity, low attenuation, flexibility and durability. Fiber cables are utilized to transmit Internet communication, telephone and cable television
signals. Information can be transmitted over long distances due to the very low attenuation of optical fibers. They also offer very high data capacities and can support many different multiplexing architectures. Hence they are used for long-haul networks as well as high-speed LAN applications in hyper data centers.

**Medical imaging**

Optical fibers as light guides can also be used for medical imaging. The endoscope is a very familiar tool that allows the device to probe the body through some small holes and capture internal images to help in complex surgeries as well as minimally invasive procedures. The endoscope is composed of a flexible, thin and long tube, with a lens or camera at the end of the tube. The image can also be captured and transmitted via fiber bundles.

**Optical sensors**

Optical fibers are also used for sensing and control applications such as temperature, pressure, level, flow, strain, shock, voltage or current etc. Optical fiber sensors offer many desirable characteristics such as small size, low weight, and immunity to radio frequency and electromagnetic interference.

**1.3 Optical Fiber**

**1.3.1 Fiber Construction**

The optical fiber is composed of core and cladding layers that are generally made of glass (SiO2). Optical fiber construction is shown in figure 1.3 and the cable structure is shown in figure 1.4. In order to protect the optical fiber, an outer layer of nylon is frequently added outside the cladding [8]. Finally optical fibers are wrapped in an optical cable, which often contains multiple optical fibers. The optical fibers in an optical cable are generally housed in loose tubes with fillers. The center of the cable
is comprises a steel wire, which is used to increase mechanical strength, while the outermost layer is composed of a protective jacket.

**Figure 1.3:** The structure of optical fiber

**Figure 1.4:** The structure of optical cable

In summary, an optical fiber is a coaxial cylindrical dielectric waveguide with a core layer of refractive index $n_1$ and a cladding layer of lower refractive index $n_2$. The main component of the core material is doped silica (SiO2) with a purity of 99.999%. The remaining ingredients may include minimal amounts of dopants such as germanium dioxide (GeO2) used to change the refractive index of the core. As shown in figures 1.5 and 1.6, the core diameter (2a) typically varies between 8~100μm. Generally, the material used for cladding layer is also SiO2. It has an outer diameter (2b) of 125μm [9]. In order to enhance the flexibility, mechanical strength and durability of the optical fiber, the cladding layer is tubed in a coating layer that consists of a polymer material of epoxy resin and silicone rubber. The light or the optical signal undergoes total internal reflection at the core and the cladding interface.
The cladding layer provides a reflective surface and light isolation. Most of the optical energy propagates within the core. According to the radial distribution of the refractive index profile, the optical fiber can be divided into the step index fiber (SI) and the graded index fiber (GI) [10]. The refractive index profile of the core of the step index fiber remains same \( n_1 \) over the entire core region, and then goes down to the cladding index \( n_2 \) in a unit step, as shown in figure 1.5. On the contrary, the index of refraction \( n_1 \) of the graded index fiber varies radially within the core region. The refractive index \( n_1 \) is highest at the center of the fiber core or the origin of the fiber and gradually decreases, upon moving radially outwards in a parabolic shape, until the cladding index reaches \( n_2 \). This is shown in figure 1.6.

![Figure 1.5: The layout of step index fiber](image1)

![Figure 1.6: The layout of graded index fiber](image2)
The optical fibers could also be classified in according to the number of modes supported by the fiber namely the multi-mode fiber (MMF) and single mode fiber (SMF), as shown in figure 1.7. Multi-mode fibers support multiple modes of light while the single mode fibers support only the fundamental mode of light [11]. Figure 1.7 and 1.8 show the ray trajectories within the cores of the two types of fiber. The single mode fiber has only one mode which propagates in a straight line trajectory. The multi-mode fiber allows multiple modes. Each mode follows a different trajectory. Longer path lengths are associated with higher-order as compared to the lower-order mode. Hence the higher order modes take longer transit time leading to propagation delay between the different modes. Therefore propagation of multiple modes causes broadening of the output pulse as compared to the input pulse in MMF.

Figure 1.7: Comparison with multimode fiber and single mode fiber

Figure 1.8: Comparison with multimode fiber and single mode fiber in 3D model
1.3.2 Fiber Connectors

A fiber connector is a physical interface that is often used to connect fiber cable to optical transceiver modules or to connect fiber patches. There are several standard types of connectors such as ST, LC, FC, and MPO. These are shown in figure 1.9.

![Fiber Connectors](image)

Figure 1.9: Four types common optical fiber connecter : (a) Straight Tip (ST), (b) Lucent Connector (LC), (c) Ferrule Connector (FC) and (d) Multiple-Fiber Push-On (MPO).

1.3.3 Operating Principle of Optical Fiber

The refractive index is the fundamental optical parameter. The refractive index of vacuum/air is 1 while the refractive index is glass approximately 1.5. The speed of light in a given material varies with the refractive index of that material. In free space, the speed of light is \( c = 3 \times 10^8 \text{ m/s} \). The ratio of the speed of light in free space to the speed of light in a material of index refraction ‘n’ is given by

\[
n = \frac{c}{v}
\]

(1.1)

According to the ray theory, the principle of operation of optical fiber transmission is primarily based on the law of refraction, Snell’s law and total internal reflection (TIR) [12]. When light travels in the same material, light propagates in a straight line. However, when a light ray is incident from a medium of higher refractive index \( n_1 \),
into a medium with a lower refractive index $n_2$, some portion of the incident light may be reflected back into the medium $n_1$, while a portion of the incident energy may be transmitted into the second material and undergo refraction, as shown in figure 1.10. The angle $\theta_i$ between the incident light and the normal plane is called the incident angle. The angle $\theta_r$ between the reflected beam and the normal plane is called the reflection angle, while the angle $\theta_t$ between the refracted light and the normal plane is called the refraction angle. Ibn Sahl’s law of reflection also known as Snell’s law [13] offers the relationship between the different angles and the refractive indices of the media. The relationship is presented by equation 1.2.

$$\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_2}{n_1}$$

(1.2)

Figure 1.10: Refraction and reflection of light ray at a material boundary

In equation (1.2), when $n_1 > n_2$, the transmitted angle $\theta_t$ is greater than incident angle $\theta_i$. When the incident angle equals the critical angle $\theta_c$, the transmitted angle $\theta_t$ equals $90^\circ$, and the transmitted beam undergoes total internal reflection (TIR), it propagates along with the interface, the denominator becomes 1, and the equation 1.2 can be rewritten as equation 1.3.

$$\sin \theta_c = \frac{n_2}{n_1}$$

(1.3)
1.3.4 Light Propagation in Fibers

A step index multi-mode fiber has a typical uniform refractive index fiber and its refractive index profile can be expressed as

\[
n = \begin{cases} 
  n_1, & 0 \leq r \leq a \\
  n_2, & a < r \leq b 
\end{cases} \quad (n_1 > n_2)
\]  

(1.4)

where \( r \) is the radial coordinate of the fiber, \( a \) is the radius of the core layer, \( b \) is the radius of cladding layer, and the refractive indices \( n_1 \) and \( n_2 \) of both the core and cladding regions remain constant within the region and the refractive index undergoes a step change at \( r = a \). The step index fiber can support two types of ray propagation namely the meridional ray (MR) and the skew ray (SR).

**Meridional Ray**

Meridional ray refers to light transmit through the meridian plane, intersecting the axis of the fiber core [14]. The meridian plane refers to the plane passing through the central axis of the fiber. Obviously, there are countless ways to intersect the meridional plane, and the trajectory of the meridional ray is a series of polylines in the meridian plane, as shown in figure 1.11.

![Figure 1.11: The meridional rays within the core of a step index fiber](image)

**Skew Ray**

Skew ray or helical ray refers to light that does not intersect the meridional plane [10]. It is neither parallel and nor does it intersect the fiber axis, therefore it is not limited to a single plane. The trajectory of the skew ray is a series of spatial helical lines which can have either right-handed rotation or left-handed rotation. A given
skew ray propagation tends to be equidistant from the central axis of the fiber as it propagates within the cylindrical geometry, where \( r_0 \leq r_{ic} \leq a \). The projection of the skew ray at the end face of the fiber is shown in figure 1.12. The cylindrical surface \( (r_{ic} = r_0) \) is called the inner defocusing surface. The electromagnetic field exhibits a standing wave in this range. The azimuthal angle \( \theta_\phi \) is between the projection line of the light on the end surface of the fiber and the tangent at reflection point. Figure 1.13 presents the output pattern of the skew ray when projected on a screen.

Figure 1.12: The skew rays within the core of a step index fiber
1.3.5 Numerical Aperture of Fiber

A step index fiber has the refractive index $n_2$ at the cladding and $n_1$ ($n_1 > n_2$) at core. The difference between $n_1$ and $n_2$ directly affects the coupling performance of the fiber. The core-cladding index difference $\Delta$ [15] is given by

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$ (1.4)

For most communication grade optical fiber, $n_1 \approx n_2$, therefore equation 1.4 can be simplified to

$$\Delta = \frac{n_1 - n_2}{n_1}$$ (1.5)

The numerical aperture (NA) of an optical fiber represents the light gathering capacity of the fiber and it can be mathematically expressed as,

$$NA = n_0 \sin \theta_0 = \sqrt{n_1^2 - n_2^2} \approx n_1 \sqrt{2\Delta}$$ (1.7)
The significance of the numerical aperture of the fiber is to characterize the ability of the fiber to capture optical power. In other word, the fiber can only receive and propagate optical energy that is incident within the acceptance cone of the half cone angle $\theta_0$ as shown in figure 1.14.

![Figure 1.14: Ray defining the numerical aperture](image)

The optical fiber normalized frequency parameter [19] is defined as,

$$V = \frac{2\pi a}{\lambda} \sqrt{(n_1^2 - n_2^2)} = \frac{2\pi a}{\lambda} NA \quad (1.9)$$

where $a$ is the radius of core, and the $\lambda$ is the wavelength of incident light. The fiber normalized frequency determines the number of modes that can propagate in the fiber. Obviously, when the wavelength and refractive index parameters are determined, the number of modes allowed in the fiber is related to the core diameter. Therefore, the core of the multi-mode fiber is large as compared to the core of the single mode fiber. In a step index fiber, if $V < 2.045$, it can only propagate a single mode, which called a fundamental mode.

### 1.3.6 Attenuation and Dispersion

**Attenuation**

In an optical fiber communication system, the optical power received by the detector has to be greater than a certain threshold level to ensure error free operation of the communication link. Hence the attenuation of the fiber is an important parameter.
Attenuation in optical fibers can be attributed to three main factors: absorption, scattering, and bend losses. In general, the transmitted optical power $P$ in the optical fiber is attenuated over a propagation distance $z$, and can be represented by

$$\frac{dP}{dz} = -\alpha P$$

(1.10)

where $\alpha$ is the attenuation coefficient. If $P_{in}$ is input power in length $z$ of optical fiber, the optical power of output is

$$p_{out} = P_{in}e^{\exp(-\alpha z)}$$

(1.11)

where $\alpha$ is expressed in dB/km, the attenuation coefficient is

$$\alpha = \frac{1}{L} 10 \log_{10} \frac{P_{in}}{P_{out}}$$

(1.12)

Glass ($\text{SiO}_2$) is the primary material used optical fibers. The absorption of optical energy in materials can be divided into intrinsic and extrinsic absorptions. Intrinsic absorption in glass is incredibly intense in the ultraviolet light region or the short wavelength band of the electromagnetic spectrum. The intrinsic absorption limits the operating wavelength in typical optical fiber communications systems. Extrinsic absorption is affected by impurities that come from metallic and hydroxyl ions. Intrinsic Rayleigh scattering follows a characteristic $\lambda^{-4}$ dependence so the influence of Rayleigh scattering becomes pronounced with decreasing wavelength as shown in figure 1.15.

Figure 1.15: Attenuation of light propagation is affected by Rayleigh scattering
Fiber bending is another cause of attenuation. Optical fiber bending can be classified into macrobends and microbends. Macrobend losses refer to large-scale bending. Optical fibers are susceptible to microbending due to coatings of the protective layer [7]. Optical bending not only causes attenuation but also reduces the tension of the fiber.

All the above factors contribute to the total losses of the fiber. The typical silica fiber attenuation curve is shown in figure 1.16. The attenuation at short wavelength region is caused by scattering while infrared absorption determines the attenuation in the long wavelength region.

![Attenuation Curve](image)

**Figure 1.16: Optical fiber attenuation curve with wavelength and optical fiber spectrum windows (Adopted from ref.7)**

The glass fiber has relatively higher attenuation within the range of 800 ~ 900nm, so this window is only suitable for short and medium distance communications. Multi-mode fiber usually use light source within this wavelength range, also called the first window. In the wavelength range of 1260 ~ 1675nm, the attenuation is smaller than the first window. The OH ion absorption peaks near 1400nm, thus the second window and the third window form around 1300nm and 1550nm respectively. Six spectral bands are often used in optical fiber communication within the 1260 ~ 1675nm region as shown in table 1.2.
Table 1.2: Spectral band designations used in optical fiber communication  
(Adopted from ref. 7)

<table>
<thead>
<tr>
<th>Name</th>
<th>Designation</th>
<th>Spectrum (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original band</td>
<td>O-band</td>
<td>1260 ~ 1360</td>
</tr>
<tr>
<td>Extended band</td>
<td>E-band</td>
<td>1360 ~ 1460</td>
</tr>
<tr>
<td>Short band</td>
<td>S-band</td>
<td>1460 ~ 1530</td>
</tr>
<tr>
<td>Conventional band</td>
<td>C-band</td>
<td>1530 ~ 1565</td>
</tr>
<tr>
<td>Long band</td>
<td>L-band</td>
<td>1565 ~ 1625</td>
</tr>
<tr>
<td>Ultra-long band</td>
<td>U-band</td>
<td>1625 ~ 1675</td>
</tr>
</tbody>
</table>

**Dispersion**

Optical fiber dispersion mainly includes intermodal delay, chromatic dispersion, and polarization mode dispersion. The modal dispersion exists in multi-mode fibers as different modes of light have different group velocities. It results in different arrival times for different modes as they reach the end of the optical fiber leading to a propagation delay or modal dispersion. Thus, the output pulse is broadened as compared to the input pulse, as shown in figure 1.17. The broadening time between the fastest mode and the slowest mode over a propagation length $L$ is known as the modal dispersion of the optical fiber and is given by

$$
\Delta T = T_{\text{max}} - T_{\text{min}} = \frac{L n_2^2}{c n_2} \Delta \approx \frac{L n_2^2}{c} \Delta
$$

(1.13)
1.4 Optical Transmitter

1.4.1 Structures of Laser and LED

The optical transmitter converts the input electrical signal into a corresponding optical signal and sends this optical signal to an optical fiber. The main component of the optical transmitter is a light source composed of either a laser diode (LD) or a light emitting diode (LED) [3].

Laser diode uses semiconductor material to generate laser light. The principle is to achieve stimulated emission between the energy bands (conduction bands and valence bands) of semiconducting materials. Population inversion is required to achieve stimulated emission light.

A light emitting diode (LED) is a type of semiconductor diode that converts electrical energy into optical. The semiconductor diode generate spontaneous emission of fluorescence. The light emitted by the LED is incoherent with broad spectral width (30 ~ 60nm) and large divergence angle.
Multi-mode step index fiber (MMF) and graded index fiber both can use LEDs as light sources. This system mainly works in the short wavelength or the first window (0.8 ~ 0.9μm). Use laser diode (LD) is relatively expensive and increases the complexity of the circuit. Therefore, for long-haul and high capacity communication systems, LD works with multi-mode GRIN fiber or a single mode fiber in O-band. The combination of the single mode fiber (SMF) and single longitudinal mode laser diode can work in low loss, long wavelength regions such as C-band and L-band, and can achieve the maximum bit rate and distance (BL). Table 1.3 summarizes some common parameters of semiconductor sources used in optical fiber communication.

Table 1.3: The typical characteristic parameters of semiconductor diodes using for optical fiber communication (Adopted from ref.7)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LEDs</th>
<th>Laser diode</th>
<th>Single mode laser diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral width (nm)</td>
<td>20 ~ 100</td>
<td>1 ~ 5</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Rise time (ns)</td>
<td>2 ~ 250</td>
<td>0.1 ~ 1</td>
<td>0.05 ~ 1</td>
</tr>
<tr>
<td>Modulation bandwidth</td>
<td>&lt; 300</td>
<td>2000</td>
<td>6000</td>
</tr>
<tr>
<td>Coupling efficiency</td>
<td>Low</td>
<td>Fair</td>
<td>High</td>
</tr>
<tr>
<td>Adapted fiber</td>
<td>MMF</td>
<td>MMF and SMF</td>
<td>SMF</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td>Application</td>
<td>Medium distance</td>
<td>Long distance</td>
<td>Ultra-long distance</td>
</tr>
<tr>
<td></td>
<td>Medium speed</td>
<td>High speed</td>
<td>Ultra-high speed</td>
</tr>
</tbody>
</table>

1.4.2 Modulation and Coding

The optical transmitter converts electrical signal into optical signal via modulation. At present, there are two commonly used schemes, the direct modulation, and the indirect modulation, as shown in figure 1.18. On-off keying (OOK) is the most common modulation method used in fiber-optic communication systems.
Figure 1.18: Two modulation approaches: Direct modulation & Indirect modulation

1.5 Optical Receiver

The optical receiver converts the received optical signal back into electrical signal at the end of optical fiber [6]. Figure 1.19 presents the block diagram of an optical receiver. It consists of a photodetector and a demodulator that serves as a signal processor. The driving circuits is used primarily for the purposes of biasing the receiver circuit.

Figure 1.19: The block diagram of optical receiver
1.5.1 PIN Photodiode and APD

The optical receivers in an optical fiber communication system, generally use semiconductor based PIN photodiode or the Avalanche photodiode (APDs) for transduction of the received signal.

The main difference between a pin diode, and a standard pn diode, is the intrinsic (i) region that is added between p and n regions, to form a larger depletion region. The intrinsic region is relatively wide, 5 ~ 50μm, which allows absorption of most of photons, as shown in figure 1.20. If the incident photon of energy $h\nu$ exceeds the bandgap energy $E_g$, and the depletion region absorbs the photon, an electron-hole pair can be generated. Due to the reverse bias applied to the pn junction, the photo generated electron-hole pair is swept across the junction and the photocarriers establish a current flow in the external circuit. The resultant current flow is called the photocurrent $I_p$. When the incident optical power changes, the photocurrent $I_p$ (sometimes also called the photodetector current $I_{det}$) also changes linearly, thereby converting the optical signal into a current, which leads to a voltage across a resistor.

The quantum efficiency $\eta$ is the number of the electron-hole pairs generated per incident absorbed photon of energy $h\nu$ and is given by

$$\eta = \frac{I_p/q}{P_{in}/h\nu}$$

(1.14)

Where $I_p$ is the photocurrent generated by a steady-state optical power $P_{in}$ that is incident upon the photodetector.

The responsivity of a photodiode is the ratio of generated photocurrent and incident optical power and is given by

$$R = \frac{I_p}{P_{in}} = \frac{\eta q}{h\nu} \approx \frac{\eta \lambda}{1.24}$$

(1.15)

where electron charge $q = 1.6 \times 10^{-19}$C, Planck’s constant $h = 6.63 \times 10^{-34}$ J \cdot s, and frequency of incident photons is represented by $\nu$. 
Avalanche photodiodes are similar to photodiodes that provide a built-in gain owing to a relatively large biasing potential. Incidents photons generate electron-hole pairs are accelerated while being swept across a high electric field region of the APD obtaining sufficient energy to knock off additional electron-hole pairs from atoms in the lattice. This electron-hole pair generated by impact ionization is called a secondary electron-hole pair. The new secondary electrons and holes pairs are accelerated as they move through the high electric field region, and may collide with other atoms to result in multiple collisions and ionization. This process tends to cause a rapid increase of photo-carriers due to avalanche effect. In short, the APD is a highly sensitive photodetector that utilizes the avalanche effect to multiply the photocurrent.

The avalanche multiplication process is a complex random process. Usually, the average avalanche multiplication ‘M’ is represented by

$$M = \frac{I_M}{I_P}$$

(1.16)

Where $I_M$ is average value of the total multiplied output current and $I_P$ is the primary un-multiplied photocurrent.

### 1.5.2 Signal to Noise Ratio (SNR)

As a signal passes through a system it undergoes change and degradation. There are two main causes of signal degradation, called the thermal noise and the shot noise.
Thermal noise, also known as Johnson noise or Nyquist noise, is generated within the load resistance $R_L$ of photodetector. The electrons in any resistor are not static. They continuously move due to thermal energy, even without an applied voltage [16]. The thermal noise current is always superimposed on the signal current generated by the photodetector.

In the photodetector, the incident light signal generates discrete charge carriers. Each carrier contributes a unit charge pulse or current pulse to the total current. This random current pulse causes the current to fluctuate, resulting in the shot noise.

The signal to noise ratio (SNR) is the ratio of the average signal power to the noise power, which determines the performance of the optical receiver and is given by

$$\frac{S}{N} = \frac{i_P^2}{2q(I_P + I_D)F(M)B_e + 2qI_LB_e + 4k_BT\Delta f} \quad (1.17)$$

1.5.3 BER and Eye Diagram

The bit error rate defines the probability that a bit is misjudged by the decision circuit of the optical receiver. The bit error rate (BER) reflects the communication quality of an optical fiber communication system. High quality optical fiber signal usually require the bit error rate to be lower than $1 \times 10^{-9}$.

The photodetector converts the optical signal into electrical signal. The decision circuit samples the electrical signal and determines whether the bit value is 1 or 0. The decision circuit compares the value of the sample with the threshold value $I_D$. If $I > I_D$, it determines the bit to be 1, and if $I < I_D$, it determines the bit to be 0.

However, under the influence of noise of the optical receiver can erroneously determine a 0 bit as a 1 bit when $I < I_D$. Similarly, a 1 bit may be erroneously judged as a 0 bit when $I > I_D$. Therefore the error probability is defined as

$$\text{BER} = P(1)P(0 | 1) + P(0)P(1 | 0) \quad (1.18)$$

Where $P(1)$ and $P(0)$ are the probabilities of receiving “1” bit and “0” bit. $P(0 | 1)$ indicates the probability of “1” bit being erroneously determined as “0” bit while
\( P(1 | 0) \) indicates the probability of “0” bit being erroneously determined as “1” bit. Due to the probabilities of occurrence of “1” bit and “0” bit are same, so the BER is given by

\[
BER = \frac{1}{2} [P(0 | 1) + P(1 | 0)]
\]  

(1.19)

Finally, BER can be related to the Q factor as shown by equation 1.20.

\[
BER = \frac{1}{2} erfc \left( \frac{Q}{\sqrt{2}} \right) \approx \frac{\exp(-Q^2/2)}{Q \sqrt{2\pi}}
\]

(1.20)

where Q factor is given by

\[
Q = \frac{I_1-I_0}{\sigma_1+\sigma_0}
\]

(1.21)

Figure 1.28 shows that BER changes with Q factor. As Q increases, the BER decreases. When Q > 7 BER < 10^{-12} and when Q=6, BER \approx 10^{-9}.

Figure 1.21: The relation between BER versus Q factor (Adopted from ref.7).

The oscilloscope is usually used to observe the waveform of the received signal to analyze the effect of inter-symbol interference and noise on the system performance. The eye diagram is generally used for this purpose. The eye diagram is generally obtained by cumulatively displaying the bits of the serial signal collected using the afterglow method. The shape of the superimposed figure looks similar to the eye, hence it is named as the eye diagram. A complete eye diagram basically contains 8
types of bit pattern from “000” to “111”. The 8 types of bit pattern are randomly added to form an eye diagram as shown in figure 1.22.

![Eye Diagram](image)

Figure 1.22: Eight types of bit pattern (000, 001, 010, 011, 100, 101, 110, 111) are superimposed together to obtain an ideal eye diagram.

In the ideal case of no inter-symbol crosstalk and noise, the waveform has no distortion, and each symbol will overlap. The oscilloscope shows a clear and bright “eye” that is mostly open. When there is cross-talk between the signals, the waveform has distortions and the trace of the eye pattern becomes unclear. The “eye” starts to close slightly. Therefore, the size of the "eye" opening represents the degree of distortion and reflects the strength of inter-symbol interference. It also indicates that the eye diagram can show the influence of inter-symbol interference and noise, and can be used to evaluate the quality of an optical fiber communication system.

Figure 1.23 shows an experimental eye diagram, generated with the help of a TXFP transceiver operating at 10 Gbit/s. Many important communication parameters can be observed on the screen, such as the SNR, the average rise time, the fall time, jitter and average power. Due to the superimposition of multiple signals, the signal line of the eye pattern becomes thicker and messy and the eye opening gets smaller. Therefore, the eye diagram also reflects the impact of noise and jitter on the signal.
The maximum distance of the blank area on the horizontal axis in one eye is called Eye Width. The eye width can reflect the stability of signal on the transmission parameters such as timing, synchronization, and jitter effects, etc. Similarly, the maximum distance of the blank area on the vertical axis in one eye is called Eye Height. The eye height reveals the noise margin of the signal on the transmission line. The extinction ratio is another important parameter. The extinction ratio defines the ratio of the average transmitted optical power of all "1" codes to the average transmitted optical power of all "0" codes, expressed in dB. The extinction ratio directly affects the sensitivity of the optical receiver.

![Figure 1.23: The eye diagram of 10 Gbit/s XFP Transceiver formed by digital communication analyzer (DCA)](image)
1.6 Optical Transceiver Module

The Optical transceiver module consists of optoelectronic devices, functional circuits, and optical interfaces [14]. The optoelectronic device includes a transmitting unit (TX) and a receiving unit (RX). The function of the optical transceiver module is to perform photoelectric signal conversion. The TX converts the electrical signal into an optical signal, and help launch the signal into the carrier optical fiber. The RX converts the optical signal back into an electrical signal. Based on the different packaging form factors, Small form-factor pluggable (SFP), Tunable Small Form Factor Pluggable (TXFP), and the Quad Small Form-factor Pluggable (QSFP) are widely used in the commercial optical communication system. 10 Gbps TXFP operating at C-band and 100 Gbps CWDM4 QSFP are shown in figure 1.24.

Figure 1.24: The 10 Gbps TXFP and 100 Gbps CWDM4 QSFP

1.7 Optical Power Budget

1.7.1 Mechanical Alignment

Many factors can cause the loss of connectivity in an optical fiber based network. Mechanical misalignment are one of the main reasons. The four types of misalignments than can commonly occur between fibers, are shown in figure 1.25. An ideal fiber to fiber joint requires good lateral and angular alignments, nice and clean end face contact, and also requires the end surface of fiber to be smooth and
parallel to each other [7,17]. In addition, coupling efficiency can reduce when optical fibers with different numerical apertures, or different core diameters, are connected to each other.

![Diagram of mechanical misalignment and non-ideal situations](image)

Figure 1.25: Four type of mechanical misalignment and non-ideal situations that can occur between two joint fibers

The lateral misalignment loss is from the non-overlapping part of the transmitting fiber and the receiving fiber core in a multi-mode step index fiber. The coupling efficiency $\eta$ is the ratio of the overlapping area to the core area, and the coupling efficiency is defined by

$$\eta = \frac{2}{\pi} \left\{ \arccos \frac{d}{2a} - \frac{d}{2a} \sqrt{1 - \left( \frac{d}{2a} \right)^2} \right\}$$  \hspace{1cm} (1.22)

where the coupling efficiency $\eta$, in decibels, is given by

$$L = -10 \log \eta$$  \hspace{1cm} (1.23)

The coupling losses due to angular misalignment in multi-mode step index fiber is given by

$$L = -10 \log \left\{ \cos \theta \left\{ \frac{1}{2} - \frac{1}{\pi} p(1 - p^2)^{1/2} - \frac{1}{\pi} \arcsin p - q \left[ \frac{1}{\pi} y(1 - y^2)^{1/2} + \frac{1}{\pi} \arcsin y + \frac{1}{2} \right] \right\} \right\}$$
where
\[ p = \frac{\cos \theta_A (1 - \cos \theta)}{\sin \theta_A \sin \theta} \]
\[ q = \frac{\cos^3 \theta_A}{(\cos^2 \theta_A - \sin^2 \theta)^{3/2}} \]
\[ y = \frac{\cos^2 \theta_A (1 - \cos \theta) - \sin^2 \theta}{\sin \theta_A \cos \theta_A \sin \theta} \]

When there is gap between the end faces of the two fibers, it causes two different types of losses. The first type is longitude misalignment. Due to the gap between the end faces, some of the emitted light could not be intercepted by the receiving fiber. As the gap increases, the receiving fiber loses more power due to beam divergence.

The fiber coupling loss due to the longitudinal misalignment is given by
\[ L = -10 \log \left( \frac{a}{a + s \tan \theta_A} \right)^2 = -10 \log \left[ 1 + \frac{s}{a} \sin^{-1} \left( \frac{NA}{n} \right) \right]^{-2} \]  \hspace{1cm} (1.25)

The second loss is due to the fact that the fiber and the gap are made of different materials with different indices of refraction \( n_1 \) and \( n_2 \) leading to losses due to Fresnel reflections. As a result the power coupling into the fiber reduces by
\[ R = \left( \frac{n_1 - n_2}{n_1 - n_2} \right)^2 \]  \hspace{1cm} (1.26)

1.7.2 The Coupling of Source to Fiber

The coupling efficiency from the light source to the fiber is defined as
\[ \eta = \frac{P_i}{P_s} \]  \hspace{1cm} (1.27)

where \( P_i \) is the input power of the fiber, and \( P_s \) is the power emitted from the light source. There are several reasons for optical power coupling losses, including losses due to reflection, area mismatch, packaging, and numerical aperture. Some of these are illustrated in figure 1.26.
Figure 1.26: The coupling loss of light source
References


Chapter 2
Spatial Division Multiplexing Technology

2.1 Multiplexing Introduction

Light operates at very high frequencies and the optical fiber offers a low-loss window that has a total width of about 200nm, hence optical fibers offers a huge bandwidth, potentially approaching 40 THz. Multiplexing technologies can enable better use of the this potential bandwidth. At present popular multiplexing technologies for optical fiber communication system [1, 2] include time division multiplexing (TDM), wavelength division multiplexing (WDM) while polarization division multiplexing (PDM) [3] and spatial domain multiplexing, also known space division multiplexing (SDM) have started to gain acceptance. The main optical fiber multiplexing technologies are shown in figure 2.1.

![Figure 2.1: Main Multiplexing technologies in optical fiber communication system](image)
2.1.1 Time Division Multiplexing (TDM)

Time division multiplexing (TDM) is a widely used technique [4]. It divides the communication bandwidth into time intervals. Each independent channel occupies a certain interval so that each channel can transmit in a given order. TDM is a mature multiplexing scheme and it is commonly used in telecommunication and optical communication systems. An electro-optical time division multiplexed system that combines inputs from multiple sources into a single optical carrier, where the transmitted and received signals carry their time stamps, is shown in the figure 2.2.

![Block diagram of time division multiplexing](image)

Figure 2.2: The block diagram of time division multiplexing

2.1.2 Code Division Multiplexing (CDM)

Code division multiplexing (CDM) relies on the different codes to distinguish the original signals. Each user in the optical fiber communication system based on optical code division multiplexing has a unique address code. This code is one of a set of orthogonal codes. Therefore, optical transmitter modulates the data of the address code while the optical receiver demodulates the same address code, thereby realizing the desired combination [5].

2.1.3 Wavelength Division Multiplexing (WDM)

The optical wavelength division multiplexing technology can couple optical channels of different wavelength into a single optical fiber through a multiplexer for simultaneous transmission. At the receiving end, the optical channels of the various wavelengths are separated by a demultiplexer or a color filter to ensure that proper
colored signals are routed to the appropriate optical receiver. There are two subtypes of WDM systems, the coarse wavelength division multiplexing (CWDM) and the dense wavelength division multiplexing (DWDM) [6, 7].

In long-distance optical fiber communication networks WDM increases the total bit capacity. Figure 2.3 shows the schematic diagram of a point-to-point large-capacity WDM link where a multiplexer is used to combine the output signals of multiple transmitters operating at their respective wavelengths (or frequencies/colors) and then transmit the multiplexed signals to a single optical fiber link. At the end of the fiber link, each channel is sent to their respective receiver after de-multiplexing. For channels with bit rates B1, B2, B3…Bn that are simultaneously transmitted over a single fiber of length l, the total bit rate-distance product is given by

\[ BL = (B_1 + B_2 + B_3 + \cdots + B_n) \times L \]  

(2.1)

If the bit rate of all channels is equal, the system capacity can be increased N times [8, 9].

![Block diagram of wavelength division multiplexing](image)

Figure 2.3: The basic block diagram of wavelength division multiplexing

2.1.4 **Polarization Division Multiplexing (PDM)**

Light is an electromagnetic wave. The direction of its electric field is called the polarization of light and it could be in the ‘x’ or ‘y’ planes. Polarization division multiplexing (PDM) is a physical layer multiplexing technique that allows the use of
two waves in orthogonal polarization states to transmit two independent channels at the same carrier frequency. In a polarization multiplexed communications systems, optical channels of two orthogonal polarization states are multiplexed together and transmitted over an optical fiber communication link [10].

2.2 Spatial Domain Multiplexing (SDM)

As early as 2001, the Photonics Laboratory of Florida institute of technology invented a novel multiplexing technology, called Spatial domain multiplexing (SDM) [11]. SDM is a multiple-input and multiple-output (MIMO) architecture that can increase the bandwidth and extend the data capacity of a standard multimode fibers [12,13]. The SDM technology is different from the space division multiplexing that is based on a multi-core fibers and is akin to laying down multiple fibers. SDM allows several optical channels of same wavelength or different wavelengths to be incident at the end face of the carrier fiber at different incident angles (or input angles), to spatially modulate the channels over a single carrier fiber. Because the SDM channel follow skew ray or helical trajectories their screen projection, at the output end of the carrier fiber, forms concentric donuts shaped circular rings that are independent of each other, where each ring represents a separate and independent optical channel. The optical energy of the independent SDM channel co-propagate with other SDM channels by occupying a different radial location on the fiber core. The architecture of SDM is similar to other multiplexing systems, and a multiplexer or beam combining module (BCM) is added at the input side to allow radially separated co-propagation of incident light within the fiber core [14]. At the receiver end a de-multiplexer or a beam separator module (BSM) is added to spatially filter the individual channels and to route them to separate fibers or detectors. Figure 2.4 shows the schematic diagram of the architecture of the SDM system.
The key components of SDM technology are multiplexer and demultiplexer. The SDM multiplexer is also referred to as beam combing module (BCM) which enables each SDM channel to enter the end face of the carrier fiber at different incident angles. The incident angles lie within the maximum acceptance cone angle of the fiber. The SDM system generally uses 200/230μm step index fibers with numerical aperture equaling 0.33. Using equation (1.7), the acceptance angle in air (n=1.00) is

$$\theta_A = \sin^{-1} NA = \sin^{-1} 0.33 = 19.23^\circ$$

(2.2)

Therefore, to arrange four input SDM channels in such a fiber, the input angles are typically chosen to be approximately 0°, 5°, 10°, and 15°. BCM can be constructed using many different methods, including SDM optical waveguides, lenses arrays, reflective mirror, curved surface mirrors and integrated 3D printed modules [15].

The key feature of SDM system is the formation of donut shaped concentric rings at the output end. Each SDM output ring represents an independent optical channel that can complement other optical multiplexing techniques such as WDM and TDM. Figures 2.5 and 2.6 show the experimental and simulated screen projections of the SDM output profiles. Due to the unique SDM output pattern, this multiplexing technology also poses a challenge to existing fiber optic communication systems as standard photo-detection techniques cannot be employed directly. Therefore, the demultiplexer of SDM, also known as beam separator module (BSM), should provide spatial filtering mechanism such that several circular SDM optical channels can be received by the optical receiver without interference with each other. There are many ways to implement the BSM including concentric circular semiconductor
CMOS photo-detector array, all-optical lens array, mirror based architectures, and prism based designs. Due to the different transmission modes and energy distribution of the optical channels at the input and output ends, the current Mux and De-mux architectures for SDM are generally unidirectional in nature as opposed to the Mux and De-mux of WDM systems [16,17] that tend to be bidirectional.

Figure 2.5: Different combinations of three channel SDM experimental output profile
The biggest advantage and of SDM technology is that its channels are based on the spatial division, and they tend to be completely independent and properly designed. And executed SDM system exhibits no crosstalk. Therefore, SDM technology can integrate with other multiplexing technologies to form two or three layer hybrid multiplexing schemes, at the physical layer of the network, to make full use of the bandwidth and space in an optical fibers, in order to increase the data rate and channel capacity. For example, a 6 channels SDM system can be integrated to a 120 channels DWDM system to form a two-layer multiplexing system [18]. In such a case each SDM channel will carry 120 DWDM channels. Hence the six SDM channels can carry 720 independent optical channels over a single fiber. As a result, SDM adds a new degree of photon freedom to classical optical fiber communication system. Using the SDM system combined with other multiplexing technologies, it may be possible to increase the transmission rate of optical fiber system to 10 Tb/s or higher.
Mathematical Model of SDM

The SDM modes can be mathematically represented as special cases of the Laguerre Gaussian (LG) modes. The LG beam [19] coming out of fiber into free space can be given as:

\[
LG_{p,l}(r, \Phi, z) = \frac{1}{w(z)} \sqrt{\frac{2p!}{\pi (p+|l|)!}} \left( \frac{\sqrt{2}r}{w(z)} \right)^l L_p^l \left( \frac{2r^2}{w(z)^2} \right) \exp \left( -\frac{r^2}{w(z)^2} \right) \ast \exp \left[ -jk \frac{r^2}{2R(z)} \right] \exp[-j\psi(z)] \ast \exp(j|l|\Phi) \ast \exp[-j\kappa z]
\]

where,
- \( r \) = The radial distance from the beam axis
- \( w(z) \) = Beam radius at distance \( z \)
- \( \Phi \) = the azimuthal position
- \( k \) = wave number
- \( z_R \) = Rayleigh range
- \( z \) = The distance from beam axis
- \( R(z) \) = Radius of curvature of the wavefront
- \( L_p^l \) = Associated Laguerre polynomial
- \( l \) = Topological charge
- \( p \) = Radial indices
- \( \psi \) = Gouy Phase shift

Figure 2.7: Gaussian beam wavefront (Adopted from ref. 20)
where,

\[ w(z)^2 = w_0^2 \left[ 1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2 \right] \]

\[ w_0 = \frac{\lambda z}{\pi w(z)} \]

\[ z_R = \frac{\pi w_0^2}{\lambda} \]

\[ R(z) = z \left[ 1 + \left( \frac{Z_R}{Z} \right)^2 \right] \]

\[ \psi(z) = (2p + |l| + 1) \tan^{-1} \left( \frac{Z}{Z_R} \right) \]

Equation (2.11) represents the solution of parabolic equation in cylindrical coordinates. Each mode is of the \((p, l)\) order, where \(p\) is the radial mode number and \(l\) is the angular mode number. Hence, the Laguerre-Gaussian modes are usually denoted as \(LG_p^l\) modes [21].

When \(l = p = 0\), equation (2.11) becomes the solution for the lowest order mode which is the fundamental Gaussian mode given in equation (2.12). When \(p = 0\), but \(l > 0\), the LG beams have a dark centered donut shaped output. Hence, those modes have one central mode. The annular node, \(l\) also known as topological charge creates optical vortex in the center of the optical beam and hence a phase cancellation occurs at the center of the beam given by equation (2.13). The radius of the ring gets bigger with increasing \(l\), as shown in figure 2.8. However, \(p > 0\), represents the concentric rings or number of nodes. These \(p + 1\) nodes represent the solution of zeros of Laguerre polynomials. As \(p\) goes higher, the beams get wider.

\[ LG_0^0 (r, \Phi, z) = \frac{1}{w(z) \sqrt{\pi}} \frac{2}{w(z)^2} \exp \left( -\frac{r^2}{w(z)^2} \right) \exp \left[ -j \frac{r^2}{2Z_R(z)} \right] \exp \left[ -jkz \right] \]

\[ \exp[-jkz] \]  

(2.12)
\[ LG_0^l(r, \Phi, z) = \frac{1}{w(z)} \sqrt{\frac{2}{\pi |l|!}} \left( \frac{\sqrt{2}r}{w(z)} \right)^l \exp \left( -\frac{r^2}{w(z)^2} \right) * \exp \left[ -jk \frac{r^2}{2R(z)} \right] * \exp[j\psi(z)] \exp(jl|\Phi|) \exp[-jzk] \] (2.13)

Figure 2.8: Intensity distribution and waveform of a Laguerre-Gaussian beam with \( l = 1 \) (Adopted from ref. 22)

The LG modes with azimuthal index \( l \neq 0 \), means there is a phase variation of \( 2\pi l \), which will lead to a right sized intensity distribution. SDM system carry their own OAM, which is \( \hbar / \text{photon} \). Each SDM channel is composed of a single ring represented by the donut shaped concentric \( LG_0^l \) mode. Figure 2.9 depicts 3 such SDM rings and their intensity distribution. Each output corresponds to individual input angle which leads to a certain topological charge.

Figure 2.9 LG based 3 Channel SDM model

2.3 Orbital Angular Momentum Based Multiplexing (OAMM)

Light has wave-particle duality, and each photon has energy \( E = h\nu \). In 1909, Poynting predicted that the circular polarization light has an angular momentum of
energy ratio $\sigma h$. The linear polarization of light is converted into circular polarization of light, and there is an exchange of angular momentum [23,24]. It was finally confirmed through experiments that when a half-wave plate is suspended by a quartz fiber, and a right-handed circularly polarized light is coupled into the fiber, the light that transmits to the half-wave plate changes from right-handed circular polarization to left-handed circular polarization. According to conservation of momentum, the $2h$ rotational angular momentum of each photon in the beam is transmitted to the half-wave plate [25]. The experimental results show that the torque of the half-wave plate is exactly the same as the fluctuation of the light, and quantum theory results in terms of strength and sign, confirm that the circularly polarized light has spin angular momentum (SAM).

In 1992 it was theoretically confirmed that photons can also carry orbital angular momentum (OAM). It comes from the spiral phase of the light wave, $\exp(ill\phi)$, term. The spiral wavefront will form a phase singular point distributed on the center axis of the light beam. The phase singularity has zero energy and momentum, so there is no angular momentum. Therefore, the phase singularity itself does not have orbital angular momentum, but the rays around the phase singularity have orbital angular momentum. According to the particle properties of light, each photon can have a linear angular momentum $h\overrightarrow{k}_0$. There is angular momentum $\pm h$ for circularly polarized light. When the light has a spiral phase, $\exp(ill\phi)$, it has an orbital angular momentum $lh$ [26]. Each optical mode can be expressed as a Laguerre-Gauss (LG) modal equation that is given by

$$LG_{p,l}(r, \phi, z) = E_0 \left(\frac{\sqrt{2r}}{w(z)}\right)^l L^l_p \left(\frac{2r^2}{w(z)^2}\right) \exp \left(-\frac{r^2}{w(z)^2}\right) \frac{w_0}{w(z)} \exp(-i\phi_{pl}(z)) \exp \left(i\frac{kz^2}{2q(z)}\right) \exp(il\phi)$$

(2.16)

Where $p$ is the radial node number, $w(z)$ is the beam waist size, $\phi_{pl}$ is the Gouy phase shift, $q(z)$ is the complex beam parameter, $L^l_p$ is the Laguerre Polynomials,
and \( l \) is the topological charge which tends to have an integer value. Helicity and rotation depend on the absolute value and sign of \( l \). The higher the \( l \) number, the more helical wave pattern is indicated in figure 2.10.

![Image](image_url)

**Figure 2.10:** Presentation of \( l = 0 \) (a), \( l = 1 \) (b), \( l = 2 \) (c), and \( l = 3 \) (d) for LG modes (Adopted from ref.20)

At the end of fiber, the output pattern resembles donut shaped concentric rings with larger ring radii representing larger values of \( l \). When two SDM input channels are launched into a fiber at equivalent but complementary angles, the resultant output rings will be at the same radial location and will overlap each other as both channels have the same \( l \) number, however both channel will have opposite spins, clockwise (CW) and counter-clockwise (CCW). If a thin wire is placed in front of the output end of the fiber, its shadow will show up on the output rings and the rings will have gaps due to the obstruction of the thin wire [27]. However the shadow will not follow a straight line, instead it will be twisted due to the CW and CCW spins associated with the two rings and the resultant OAM. A specially designed circular photodetector, that is segmented in to eight equal sections and has a built-in ridge, can be used to detect both the intensity as well as the direction of the OAM. Such a detector is shown
in figure 2.11. Since the outputs of the two SDM rings overlap and the two channels carry equal but opposite OAM (CW and CCW), the position of the shadow of the thin wire along with the intensity readings could be combined to detect and process the information carried by the two independent channels [27]. This enables a novel OAM based multiplexing technique that adds another degree of photon freedom to optical fiber communications systems.

Figure 2.11: A circular Photodetector divided into eight parts to detect OAM beams
References


Chapter 3
Multiplexing of SDM

3.1 Introduction BCM

The BCM is the beginning of the SDM system, and the quality of BCM is affected by many factors such as vibrations, beam divergence, and the physical space between the channels. The BCM system determines the health of SDM optical communication link and link distance. Therefore, BCM needs to have high precision to ensure that the input channels transmit into the carrier fiber with maximum coupling efficiency [1]. The angle of the input fiber, and the distance between the input fiber and the SDM carrier fiber should be determined accurately with the help of calculations and simulations, and then the system should be built in a careful and skillful manner [2]. So far, the Optronics Lab at Florida Tech has designed several types of BCM solutions. These structure include optical waveguides, fiber tubes, optical lenses & mirrors, and integrated 3D printing modules etc.

3.1.1 Lens and ABCD Matrix

In many BCM and BSM designs, light is collimated and focused into a fiber with the help of a convex lens as shown in figure 3.1. The focal length of a thin lens is defined as

\[ \frac{1}{f} = (n - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right) \]  

(3.1)

where \( n \) is refractive index of lens, \( R_1 \) and \( R_2 \) are radii of curvature of thin lens [3].
Figure 3.1: The principle of focusing and collimating of a convex lens

The beam emitted from the fiber has a divergence angle. According to the principle of reversible optical path, the divergence angle of the beam can also be considered as the maximum acceptance angle of the fiber. The divergence angle is related to the NA of the fiber, and the corresponding relationship is shown in figure 3.2.

Figure 3.2: Relationship between Numerical aperture and Acceptance angle of a fiber. (NA=$\sin \theta_A$)
Using ABCD matrix can improve computational efficiency. Figure 3.3 shows the transfer matrix in free space and the thin lens matrix [4]. Some BCM and BSM designs require thin lenses or mirrors. The dimensions of the desired lenses and the distance between the fiber and the lens could be determined with the help of the ABCD matrix.

Figure 3.3: Optical ABCD Matrix: (a) Homogeneous medium with length \( d \) and (b) Thin lens with focal length \( f \)

### 3.1.2 Mode Field Diameter (MFD)

The input fibers for SDM are usually single-mode fibers (SMF). There is often a short distance between the SMF and the SDM carrier fiber. The distance and angle between two the fibers directly affect the performance of the whole SDM system [5]. Therefore, the SDM carrier fiber needs to utilize bigger NA, as much as possible, so that the SDM system can ensure minimal power loss, even in cases of large angle of incidence. The beam divergence and the mode field diameter (MFD) of the single mode fiber are important factors to determine the distance between the fibers. MFD characterizes the energy distribution of fundamental mode in the core region of a single mode fiber. According to Petermann integral at the far field, MFD is defined by

\[
\text{MFD} = \frac{\lambda}{\pi} \sqrt{\frac{2 \int_{-\infty}^{\infty} I(\theta) \sin \theta \cos \theta d\theta}{\int_{-\infty}^{\infty} I(\theta) \sin^3 \theta \cos \theta d\theta}}
\]  

(3.2)
where $I(\theta)$ is the far-field intensity distribution of the light source with a function of the far-field angle $\theta$.

The fundamental mode has the highest intensity at the axis of the core region and gradually decreases as the distance from the axis increasing [6]. The mode field diameter generally defines the maximum distance between two points where the light intensity reduce to $1/(e^2)$ of the maximum intensity at the axis, as shown in figure 3.4. Typically, in 1310nm, the MFD is $9.2 \pm 0.5\mu m$; In 1550nm, the MFD is $10.5 \pm 1.0\mu m$.

![Figure 3.4: The mode field diameter (MFD) of singlemode fiber](image)

**3.2 The BCM with Bare Fibers and Fiber Tubes**

**Bare fibers**

In the early SDM experiments, the BCM were built by using bare single-mode fibers and placing them over a metal plate or optical slider and arranging them at different incident angles. A 3-axis adjustable slider can support a better control the input orientation and distance. The optical slider also increases the accuracy of BCM system. Taking a four-channel SDM system as an example, four input fibers are arranged at 0, 5, 10, and 15 degrees and fixed on a metal plate. The SDM carrier fiber is placed as close as possible to the four input fibers to increase the coupling
efficiency [7]. The height of the four fibers should be as consistent as possible with the SDM carrier fiber. The maximum tolerance should not exceed the core radius of the carrier fiber, otherwise it will affect the pattern and output power of the SDM ring.

Figure 3.5: The four channels BCM with bare fibers in SDM and its output profile
Figure 3.5 shows a four-channel BCM and its output profile on the screen. Figure 3.6 and figure 3.7 present results from a simulated model and output pattern produced by ZEMAX [4] with a similar BCM structure.

Figure 3.6: The 3D modeling of fiber tubes multiplexer for 4 channels SDM simulated by Zemax

Figure 3.7: Four channel output pattern and profile of SDM system using Zemax

Since there is no optical element between the input fiber and the carrier fiber, so the beam divergence of light cannot be changed [8]. Therefore, the outermost SDM channel has higher losses due to beam divergence. For example, if the diameter of core of a carrier fiber is 200\(\mu m\), and NA is 0.37. According to the equation (1.7), the maximum acceptance angle is 21.7 degrees. The input fiber is single mode fiber, so V number is less than 2.405. NA is usually smaller than 0.11. The maximum
acceptance angle or the beam divergence is 12 degrees. To minimize coupling losses, the angle of incident should satisfy the following condition

$$\theta_{IN} + \phi \leq \theta_A$$ (3.3)

where $\theta_{IN}$ is the beam divergence or maximum acceptance angle of input fiber, $\phi$ is the particular input launching angle, and $\theta_A$ is the maximum acceptance angle of SDM carrier fiber as shown in figure 3.8.

For example, the diameter of core of a carrier fiber is 200$\mu$m, and NA is 0.37. The maximum acceptance angle is 21.7 degrees. The input fiber is single mode fiber. NA is 0.11 [9]. The maximum acceptance angle or beam divergence is 6.3 degrees.

According to eq (3.3), $\phi$ should be smaller than 15°. In other word, the biggest input angle should be controlled under 15 degrees based on these conditions.

**Fiber tubes**

If there is no tubing to protect the bare fibers, the system may become very fragile and unreliable. If it is placed directly on the bench, it would not be stable for a long time. The fiber sometimes shakes due to weak mechanical vibration or airflow in the surrounding environment. It brings jitter and makes the output power unstable. Therefore the fiber tube, which is a plastic tube with a slightly larger diameter than the bare fiber, can solve this problem. The bare fiber covered with the fiber tube not only protects the fiber from breaking easily, but it also keeps the system stable. It can also allow some adjustment to the angle and distance of the input fiber [9,10]. In
addition, because the size of the fiber tube is slightly larger than the fiber, it would not stick to the cladding layer of the bare fiber. The propagation path of the light in the fiber does not change and output profile of SDM channel is not altered.

A BCM prototype that allows easy coupling to multiple scenarios is designed with the help of hollow core fiber tubes which are fixed to a rigid base at different angles. One side of the fiber tube extends out of the metal plate, and all of the extensions of fiber tubes focus on one point. The carrier fiber is placed at that point so that each input channel can couple into the SDM carrier fiber with the maximum efficiency [11]. Figure 3.9 indicates a fiber tube multiplexer for BCM in SDM system that covers input angle ranging from 0 to 25 degrees. The results of four channels SDM using the fiber tube based BCM is shown in figure 3.10. A 3D model of a similar system simulated by ZEMAX is presented in figure 3.11.

Figure 3.9: A multiple channels multiplexer with fiber tubes for SDM system
Figure 3.10: A four channels SDM output pattern created by fiber tube based multiplexer

Figure 3.11: A 3D modeling of fiber tubes multiplexer using Zemax
3.3 3D Printed BCM

The operation of a 3D printer is based on a digital model file and uses an adhesive plastic to construct an object, layer-by-layer. The SolidWorks and ZEMAX are used to setup a SDM mathematical model and simulate this SDM system. Finally, the BCM and BSM modules are implemented by 3D printing technology [4,11]. Using 3D printing technology to customize the dedicated BCM module, the alignment and fixing of fibers and optical elements is significantly simplified. Such BCM modules can greatly improve the misalignment issues and coupling efficiency. In addition, many optical aids, such as sliders and lens mounts etc., are not needed anymore. Simplified and integrated BCM and BSM prototypes are critical for the SDM system commercialization.

Currently, there are several types of 3D printed BCM designs. One of those designs is shown in figure 3.12. This model uses SolidWorks to build circular channels passing the first cube with different angles, from 0 degrees to 25 degrees. In addition, the extensions of all channels should eventually converge to one point. The size of the circular channels are slightly larger than the diameter of the input fiber. In the center of the second cube has a through-circular channel that is slightly larger than the SDM carrier fiber. The two cubes are placed on a half surrounded slide. The slides can adjust the distance between two cubes and also keep the channels of two cubes at the same height. The SDM carrier fiber inserts into the second cube and then fixed on the slide [12]. The SDM input fibers are inserted into the holes of the first cube and then pushed on the slide to adjust the distance between the two blocks. Light emitted from the input fibers can be focused on the end face of the SDM carrier fiber with different input angle. This BCM module can be designed with in small size with very good quality and the number of SDM channels on such designs can vary between 2 channels to 6 channels.
Another 3D printed BCM is designed for a two channel SDM systems operating at 1550nm wavelength. This design consists of a convex lens mount with an angle of 12 degrees, two input fiber holders, and a SDM carrier fiber holder. All of parts are finally integrated on a solid platform with the same height [13,14]. The input fiber holder of the outer channel is also tilted 12 degrees and remains coaxial with the lens holder. The layout is shown in figure 3.13.
Figure 3.13: The layout of two channels SDM system with 3D printed multiplexer. The dimensions of the convex lens can be calculated by the ABCD matrix. The spot size and beam divergence angle of the input are the primary considerations. The distance between the lens and fiber should be as short as possible to ensure quality of the beam spot. Shorter distance can also avoid excessive scattering and noise interference of the optical signal in the air. The smaller dimension of BCM module also facilitates the integration of SDM systems [15].

The input fiber is standard single mode fiber, so the NA is usually 0.11. According to eq (1.8), the beam divergence of the fiber is 6.31°. If the distance between lens and the input fiber is $d_1$, the distance between lens and carrier fiber is $d_2$ and the focal length of lens is $f$. The SDM carrier fiber has a core of 200 μm and cladding of 230 μm. The numerical aperture is 0.37, so the maximum acceptance angle is 21.7°. Because the input launching angle is 12°. According to eq (3.4), the lens should focus the beam into carrier fiber with beam divergence of 3°. According to ABCD matrix,

$$
\begin{bmatrix}
    r_2 \\
    \theta_2
\end{bmatrix} = \begin{bmatrix}
    1 & d_2 \\
    0 & 1
\end{bmatrix} \begin{bmatrix}
    1 & 0 \\
    -1/f & 1
\end{bmatrix} \begin{bmatrix}
    1 & d_1 \\
    0 & 1
\end{bmatrix} \begin{bmatrix}
    r_1 \\
    \theta_1
\end{bmatrix}
$$

$$
\begin{bmatrix}
    r_2 \\
    \theta_2
\end{bmatrix} = \begin{bmatrix}
    1 - \frac{d_2}{f} & d_1 + d_2 \left( -\frac{d_2}{f} + 1 \right) \\
    -\frac{1}{f} & \left( -\frac{d_2}{f} + 1 \right)
\end{bmatrix} \begin{bmatrix}
    r_1 \\
    \theta_1
\end{bmatrix}
$$

(3.4)
Where $\theta_1 = 6.3^\circ$, $\theta_2 = 3^\circ$, $r_1 = 5\mu m$, $r_2 = 100\mu m$. Assuming the range of $d_1$ is from 10mm to 50mm, which is also bigger than the focal length of lens. The range of $d_2$ is from 30mm to 80mm. The range of focal length of lens is from 10mm to 40mm. Calculations and optimizations select a Plano-Convex Lens (KPX076), 25.4 mm diameter N-BK7 plano-convex lens with an effective focal length of 25.4 mm [16].

Running optical simulation by ZEMAX and 3D modeling by SolidWorks, $d_1 = 31.5mm$, $d_2 = 72mm$ can guarantee the center channel and outer channel focus into the SDM carrier fiber with the maximum coupling efficiency [17]. Using the Plano lens (KXP076) can focus the input beam. The size of the beam spot would be smaller than the maximum receiving range of the carrier fiber. In addition, a clear SDM ring pattern can be obtained due to the small divergence angle [18].

This complete 3D printed BCM design is divided into a couple of steps. Firstly, using SolidWorks and ZEMAX create a 3D mathematical model, and then add fibers and lens to simulate in ZEMAX. The 3D model of SolidWorks and Zmax are shown in figure 3.14 and 3.15.

Figure 3.14: The 3D model of BCM in SolidWorks
The output intensity profile and power of two SDM rings are analyzed by ZEMAX, and to optimize the position and input angle between the fiber and lens. Exporting the corrected position data transfer to SolidWorks generates a correct 3D digital model [19]. The final 3D model is exported to ZEMAX, and simulated again. The data of fiber output are recorded as shown in figure 3.16 and table 3.1. Finally, the BCM model is printed by 3D printer. Experiments are performed with the same fiber and lens as the simulation to compare with the simulated data.

Figure 3.16: Two channel SDM output and intensity profile simulated by Zemax
Table 3.1: The parameters and output profile of each SDM channel using Zemax

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Channel 1</th>
<th>Channel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>wavelength</td>
<td>1550nm</td>
<td>1550nm</td>
</tr>
<tr>
<td>Input angle</td>
<td>1°</td>
<td>12°</td>
</tr>
<tr>
<td>Input power</td>
<td>1mW</td>
<td>1mW</td>
</tr>
<tr>
<td>Output power</td>
<td>0.92mW</td>
<td>0.88mW</td>
</tr>
</tbody>
</table>

The high resolution 3D multiplexer is printed at Florida Tech library [20] and is shown in figure 3.17. The SDM prototype is setup by that includes two input single mode fibers, a SDM carrier multi-mode fiber, and the Plano convex lens (KPX076).

Figure 3.17: The 3D printed BCM with Plano convex lens for two channel SDM
The two channel SDM output pattern and experimental results are presented in figure 3.18 and table 3.2. The BCM unit minimizes vibrations and improves coupling efficiency [20].

Figure 3.18: The output pattern of two channels SDM guided by 3D printed BCM

Table 3.2: Experimental results for SDM channels

<table>
<thead>
<tr>
<th></th>
<th>Channel 1</th>
<th>Channel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>wavelength</strong></td>
<td>650nm</td>
<td>650nm</td>
</tr>
<tr>
<td><strong>Input angle</strong></td>
<td>0°</td>
<td>12°</td>
</tr>
<tr>
<td><strong>Input power</strong></td>
<td>-2.2dBm</td>
<td>-4.8dBm</td>
</tr>
<tr>
<td><strong>Output power</strong></td>
<td>-3.7dBm</td>
<td>-9.7dBm</td>
</tr>
<tr>
<td><strong>Output profile</strong></td>
<td><img src="image1.jpg" alt="Image" /></td>
<td><img src="image2.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>
The 3D printed BCM is a convenient approach to utilize the input space efficiently. In most cases, input fibers are too close to each other causing obstructions in the input part of the system.
Reference


Chapter 4
De-Multiplexing of SDM

4.1 CMOS

Complementary Metal Oxide-Semiconductor (CMOS) is an integrated circuit design process that makes it possible to fabricate basic components of NMOS (n-type MOSFET) and PMOS (p-type MOSFET) on a silicon wafer. Because NMOS and PMOS are complementary in physical characteristics, they are called CMOS. Using a standard CMOS process, a new type of concentric photodetector array is designed, fabricated and tested in Florida Tech. This CMOS photodiode array can be used as de-multiplexer for SDM. In this design, the CMOS arrays [1,2] are arranged in a circular configuration with the ring size corresponding to the SDM output channels, as shown in figure 4.1 and figure 4.2.

Figure 4.1: N-well/P-substrate concentric CMOS

Figure 4.2: The cross section of N-well/P-substrate CMOS photo-detector
Each SDM channel is launched onto one of the ring based CMOS photodiodes in the array. Each detector in the array has an independent circuit that can generate photocurrent for data transmission. The photodiode array structure is shown in figure 4.3.

![Figure 4.3: The concentric CMOS photo-detector array](image)

There are two factors that affect the design of photodetector: transit time and junction capacitance. Transit time is the time it takes for photo-generated carriers to move through the depletion layer [3,4]. This is given by

$$t_d = \frac{w}{v_d}$$  \hspace{1cm} (4.1)

Where $w$ is the width of depletion region, and $v_d$ is the velocity of carrier drift. According to the equation (4.1), width of depletion region greatly influences the time. To achieve a high quantum efficiency, the width of the depletion should be greater than $1/\alpha_s$ (the inverse of the absorption coefficient), so that most of the light could be absorbed. On the other hand, if the depletion width is too small, photocarriers produced in the undepleted material must diffuse back to the depletion region before
being collected. Second, a too small width of depletion causes the effect of junction capacitance to become noticeable. The junction capacitance $C_j$ [3] is given by

$$C_j = \frac{\varepsilon_s A}{w}$$  \hspace{1cm} (4.2)

Where $\varepsilon_s$ is the permittivity of the semiconductor material, and $A$ is the diffusion layer area. $w$ and $C_j$ are inverse relations, a larger capacitance will result in a larger RC time constant, limiting the detector's response time.

For pin diodes, the depletion region is practically its intrinsic region. However, the CMOS depletion region depends on the external bias voltage. In order to obtain a larger bias voltage, the CMOS depletion region width is much larger than the pin’s, so the transit time is much longer. Because CMOS has a large depletion region width, it has a small capacitance. Similarly, the pin is set to a very high bias voltage, so capacitance has little effect on its performance.

The CMOS based detector is a successful de-multiplexer of SDM design [5] that directly converts optical signals into electrical signals, eliminating a lot of power loss and noise interference between the carrier fiber and the receiver. However, concentric CMOS photodetector array is not a standard optical detector. If it is used as de-multiplexer for SDM, many receivers in optical fiber communication system may not be compatible and need to be replaced, which is extremely expensive. So de-multiplexer of SDM using passive optical device has greater potential and applications.

4.2 All Optical Lens De-multiplexer

Optical to optical is De-multiplexing of SDM channels is a desirable approach. The advantage is that the optical system is easy to integrate and does not affect the structure of the communication system at the upper layers. Unlike the CMOS design the optical to optical de-multiplexing only requires a BSM to the original system.
The all optical lens de-multiplexing [6] may be designed in many different ways. The original design uses the bulk lens de-multiplexer for two channels as shown in figure 4.4. In this design, the output rings pass through a collimating lens. The collimated rings are separately focused onto two independent photodetectors using focusing lenses of different sizes.

![Figure 4.4: The bulk lens de-multiplexer for two channel SDM (adapted by ref. 6)](image)

The bulk lens de-multiplexers provide very good direction to design BSM. Since this system requires high accuracy, any misalignments may cause large losses. Therefore, a single-lens de-multiplexing solution is desired. The single lens de-multiplexer minimizes physical size while providing similar functionality [7]. Figure 4.5 explains how it works and uses.

![Figure 4.5: The multi-focal points lens de-multiplexer for two channels SDM (adapted by ref. 7)](image)

A fiber-based de-multiplexing design was also proposed in the past. This design utilizes different SDM channels to transmit signals in spatial positions of different
diameters in the fiber. Using a hollow core fiber with a separate core and cladding for the output ring to guide into separate detectors located on a bevel edged structure [8]. The design is presented in figure 4.6. The bevel allows the light to be concentrated at the tip to achieve the best coupling efficiency.

![Figure 4.6: Bevel-edged hollow fiber De-multiplexer of two ring SDM (adapted by ref. 8)](image)

### 4.3 Beam Splitter De-Multiplexer

The BSM based on the beam splitter and lens concept [9] is presented and in figure 4.7. Using a beam splitter, the power of the optical signal is equally divided into 50:50 without changing the characteristics of its output pattern. Only one of two channels carrying half of the power is allowed to pass and the other is physically blocked. The two channels are then focused onto two separate photodetectors by the help of focusing lenses. The ZEMAX simulation for such a system is shown in figure 4.8. This design has been experimentally verified for a two channel SDM system at 20 Gbit/s for systems operating at C band.
4.4 Prism De-Multiplexer

The prism based BSM selectively alters the optical path of different SDM channels in a fashion that the signal of each channel can be received completely with minimal losses and crosstalk [10]. Prism of different sizes can be used to selectively alter the light path of radially distributed SDM channels. When one side of prism is parallel to the beam, it guides the beam to turn at 90 degree. A suitable sized and properly positioned prism can make one SDM channel to turn at 90 degrees while the other
one passes through this prism and be redirected by the next bigger prism. Finally, each channel is reflected and directed to the focusing lens. Due to the different incident angles, each optical channel is focused at different point and received by separate photodetector. Figure 4.9 shows prism based de-multiplexing of four channel SDM system using Zemax. The four channels are launch at the convex lens at different angles and focused into four separate spots allowing enough space to detect and process them. The output profile is detected by a photodetector in Zemax as indicated in figure 4.10

Figure 4.9: The block diagram of combination of prisms based de-multiplexer for four channel SDM

Figure 4.10: The output profile of four channels SDM as detected by a photodetector in Zemax
Using reflections to separate the SDM channels represents a reasonable approach. However, prism has its own limitations. When SDM combines with WDM, use of prism will give rise to chromatic dispersion [11] in each SDM channel carrying CWDM or DWDM optical signals. The prism decomposes the multi-wavelength of light as shown in figure 4.11.

![Figure 4.11: The prism decomposes the different wavelength of light](image)

Therefore, based on the reflection of prism, a reflective mirror based de-multiplexer is designed. The mirror replaces prism and solves the dispersion issues.

### 4.5 Mirror with Elliptical Hole De-Multiplexer

This de-multiplexer uses a mirror with hole, collimating lens, and focusing lens to build the all optical de-multiplexer. This de-multiplexer utilizes a series of lenses and mirrors to guide and focus each channel onto individual detectors. The basic structure of de-multiplexer is presented in figure 4.12. First, the output of the SDM channels pass through a collimating lens to minimize the impact of beam divergence and to collimate each ring. The collimated beam is then incident on mirrors with centralized holes.
Figure 4.12: The architecture of the optical lens array and mirrors for SDM demultiplexer

The mirrors are arranged at 45 degree or -45 degree angles to reflect the annulus beams. The shape of hole on the mirrors is elliptical. The long axis radius of the ellipse is 1.43 times the radius of the short axis. The thickness of the mirror also needs to be taken into account. In the direction of the long axis, the radius of the left side needs to be added to the thickness of the mirror, which is slightly longer than the radius of the right side as shown in figure 4.13. For a multi-channel SDM system, the first mirror with the largest center hole causes the outermost ring to reflect 90 degrees toward a convex lens and focus onto an output fiber. Meanwhile, the remaining rings pass through the center hole due to smaller ring size than the hole.
According to the structure of figure 4.12, the four SDM channels are separated by the array of mirrors. The CAD of the mirror array and an customized mirror are shown in figure 4.14. To enhance the accuracy and stability of the de-multiplexing system, a dedicated mirror mount is designed and manufactured using 3D printer technology.

Figure 4.14: (a) The CAD layout of the mirror array and (b) a customized mirror based SDM de-multiplexer
A similar SDM system consisting of four input optical channels, an adjustable beam combination module (BCM), a carrier multi-mode fiber, the above de-multiplexer unit, and several detectors is simulated using Zemax and the simulated results are compared to the experimental output profile. Figure 4.15 shows the output profile of the four channel SDM and the intensity profile of the rings produced by Zemax.

![Diagram](image)

Figure 4.15: The output profile of a four channels SDM system and the intensity profile of the four rings in Zemax simulation

The key to any de-multiplexing technique is that each channel should be completely separable without crosstalk. If the signal has crosstalk and it interferes with another signal, it causes noise and result in a poor bit error ratio (BER). To prove the
reliability of this de-multiplexer, each channel is turned on and off and the resultant output intensity is presented in table 4.1.

Table 4.1: Four channels SDM simulated results indicate no crosstalk or interference

A complete, crosstalk free, de-multiplexer for a four channel SDM system is designed and simulated. The all optical lens array based de-multiplexer allows SDM to be used in conjunction with existing optical communications system. For example, a ten channels SDM system in conjunction with WDM to build a two layers multiplexing technique in optical fiber communication system can increase the data capacity by tenfold.
Reference

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and Photonic Applications Systems Technologies, OSA Technical Digest (CD),
Optical Society of America (2008).
Chapter 5
Two Channel SDM Communication System in C-band

5.1 Introduction
SDM offers a complete system to address bandwidth demand. The complete SDM system includes a BCM, the carrier fiber, and a BSM. The SDM system can be used independently, and can also be combined with other multiplexing technologies such as WDM and OAM etc. This chapter presents a complete optical fiber communication system based on the spatial domain multiplexing technology [1]. The system consists of two SDM channels, with each channel capable of transmitting data at 5 Gbps and 10 Gbps. The optical transmitter uses tunable small factor pluggable (TXPF) transceivers operating at C-band. The carrier SDM optical fibers is tested at three different length, 5m, 60m, and 150m to simulate LAN and data center operations. Each SDM channel is evaluated and analyzed with the help of a digital communication analyzer (DCA). The DCA can generate the eye diagram of each channel to analyze the data of communication system, including the data rate, signal to noise ratio (SNR) and bit error rate (BER).

The block diagram of the two channel SDM communication system is shown in figure 5.1. It includes the multiplexing unit, which is the BCM, the SDM carrying fiber, and the de-multiplexing unit or the BSM.
5.2 Simulation

Firstly, the SDM system is modeled and simulated by SolidWorks and Zemax [2,3]. A combination of 3D printed mount and fiber tubes are employed to build the BCM. The two input channel use single mode fibers (SMF). One side of SMF is bare, and other side has FC connector. The diameters of core and cladding of SMF are 9/125μm. The numerical aperture of fiber is 0.11, so the angle of beam divergence is 6.2°. The SDM carrier fiber is a step index multi-mode fiber. The diameter of core is 200um, and NA of fiber is 0.37. The two input channel are independently launched into the carrier fiber at incident angles of 0° and 15° using hollow core fiber tubes. The 3D model of BCM using ZEMAX is shown in figure 5.2.
First, the two SDM channel are launched into a 5m carrier fiber. In the BSM part, the mirror with the elliptical hole is used as the core component and the collimating and focusing lenses form the complete de-multiplexer of SDM. This design has been introduced previously in chapter 4. Two channels initially pass through a collimating lens to collimate the output beams and tune the ring sizes. The mirror with elliptical hole is placed behind the collimating lens. When the mirror is placed at an angle of 45° with the front surface of the beam, the elliptical cut appears as a circular hollow to the optical beam. The diameter of this hollow is slightly larger than the diameter of the center channel, but smaller than the diameter of the outer channel. Therefore, the center channel can propagate through the hollow without touching the edges of the mirror. Due to the larger diameter of the outer channel, the ring incident on the mirror surface is reflected at 90 degrees. The center beam is focused into the multi-mode fiber with the help of the focusing lens. Similarly, the outer ring is coupled into the another multi-mode fiber by a focusing lens of bigger diameter due to the larger ring size of outer channel. The 3D model of the de-multiplexing unit is simulated with the help of Zemax and presented in figure 5.3.
In ZEMAX, many photodetectors are placed in various locations to analyze any changes in ring pattern and the power of each channel at each node of the SDM system. The output pattern of two SDM channel are two concentric rings at the end of carrier fiber. Two rings are independent of each other and do not exhibit any crosstalk [4]. The output parameters and output profile of two SDM channels is presented in tables 5.1 and 5.2. The power budget of center and outer channel are also measured, and presented in table 5.3.

Table 5.1: The parameters of two channels in Zemax

<table>
<thead>
<tr>
<th>Output profile</th>
<th>Center channel</th>
<th>Outer channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1550nm</td>
<td>1550nm</td>
</tr>
<tr>
<td>Diameter of ring size</td>
<td>1.2mm</td>
<td>Outer ring: 4.1mm Inner ring: 3.2mm</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>4.28°</td>
<td>14.04°</td>
</tr>
</tbody>
</table>
Table 5.2: Combination of two SDM channels and output profiles

<table>
<thead>
<tr>
<th></th>
<th>Output profile</th>
<th>Cross section of output profile</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Center</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Outer</strong></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Center + Outer</strong></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Table 5.3: The power budget of center and outer channel

<table>
<thead>
<tr>
<th>Center Channel</th>
<th>Input</th>
<th>Output after carrier fiber</th>
<th>Output after Collimator</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (dBm)</td>
<td>1 dBm</td>
<td>-1.19 dBm</td>
<td>-1.45 dBm</td>
<td>-2.37 dBm</td>
</tr>
<tr>
<td>Output Profile</td>
<td><img src="image" alt="Center Channel Output Profile" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outer Channel</th>
<th>Input</th>
<th>Output after carrier fiber</th>
<th>Output after Collimator</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (dBm)</td>
<td>1 dBm</td>
<td>-3.29 dBm</td>
<td>-3.56 dBm</td>
<td>-5.37 dBm</td>
</tr>
<tr>
<td>Output Profile</td>
<td><img src="image" alt="Outer Channel Output Profile" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The carrier fiber used is a step index multi-mode fiber. The length of the carrier fiber is important. In theory, when the transmission distance increases, the signal would gradually weaken, and the outer channel is more affected by the length due to the longer optical path in the fiber [5]. Therefore, it is helpful to build a system and analyze the influence of the length of the carrier fiber and trace the output pattern and the power of the SDM channels through simulations. The table 5.4 represents the SDM output profile as the length of the carrier fiber is varied.
If the focal length of the focusing lens is constant, the smaller ring size, the smaller the divergence of the beam spot. Smaller spot size and divergence indicate that the ring has the ability to couple energy into a smaller diameter optical fiber, such as the OM1 fiber (62.5/125μm) or the OM3 fiber(50/125μm) [6] in a reasonably efficient manner. Therefore, the size and placement of the lens and mirror should be as small as possible and as close as possible. The simplistic designs presented here will probable develop into more integrated smaller form factors silicon photonics based light integrated circuits.

5.3 Experimental setup
Based on the simulated data, the hardware setup of two channel SDM is built as shown in figure 5.4.
The light source for this SDM system operates at C-band. Alignment of fibers and lenses is a challenge due to the invisible nature of the light source. Therefore, the setup and alignment of the system used the 650nm red light to develop the baseline for the individual components and modules, until the BCM and BSM are roughly aligned in the proper positions. However, the use the visible light is not optimum for this purpose. According to Sellmeier equation [7],

$$n^2(\lambda) = 1 + \sum_{l=1}^{M} \frac{B_l \lambda^2}{\lambda^2 - C_l}$$

(5.1)
where, \( n \) is the refractive index of material, \( \lambda \) is the wavelength, and \( B_i \) and \( C_i \) are determined Sellmeier coefficients by experiments [8]. Also, each term of sum represents an absorption resonance of strength \( B_i \) at particular wavelength \( \sqrt{C_i} \) [8].

The refractive index is divided into two parts, the real part and the imaginary part. The imaginary part is a function with wavelength. Thus the refractive index is related to wavelength of the light, and any change in operating wavelength of light source results in change in refractive indices of the core and cladding of the fiber. Similarly, the focal length of the lens also change with wavelength, and the longer the wavelength, the larger the focal length. Therefore, initial alignment of the system with a visible light source of 650nm and then switching to a source operating at 1550nm requires realignment of the distances and positions of the lenses and fibers.

The BCM part is first to be built. Two input signals generated at the TXFP transceiver launch light into two single mode fibers. Because output side of fiber is bare, fiber tubes are used to align and protect them. The two fibers are placed on separate micro-motion slides, and the center channel fiber is placed coaxially with the carrier fiber to ensure an incident angle of 0°. This SDM system uses only two channels, so the input angle of the outer channel has a wide range. In order to optimize the output pattern and power of SDM channels, the relationship between the incident angle and the output power is experimentally determined. The relationship of input power and launch angle is shown in figure 5.5. The input angle of the outer channel is set to 15°.
Figure 5.5: The relationship between launch angle and input power

The input angles of center and outer channels are 0° and 15° respectively. A fiber mount for the carrier fiber is designed using SolidWorks and Zemax to provide the same height for each fiber as shown in figure 5.6. A fusion splice machine was used to arc the input ends of the fiber to produce integrated ball lens at the end of the fiber, as shown in figure 5.7. The ball lens can produce smaller beam sizes and beam divergence to achieve improved coupling efficiency and better defined SDM rings. Finally, a BCM unit for two SDM channel is assembled using the above mentioned parts and fibers, as shown in figure 5.8.
Figure 5.6: A stable mount for BCM

Figure 5.7: Microscopic view of fiber and the ball lens produced using electrical arc

Figure 5.8: Two channel BCM for SDM
The output profile of two SDM channel with 650nm visible light is displayed in figure 5.9.

![Image](image1.png)

Figure 5.9: The output profiles for center and outer channels after carrier fiber and collimating lens using 650nm laser

The figure 5.10 shows the hardware setup of BSM unit. In the BSM part, 650nm visible laser was initially used to adjust the position of the mirror with an elliptical hole until two rings are totally separated without any crosstalk, as shown in figure 5.11. Then, they are coupled into the output fiber by the focusing lens respectively.

![Image](image2.png)

Figure 5.10: The top view of two channel BSM of SDM setup
The two output channels are coupled to the photodetector of Digital Communication Analyzer (DCA) to acquire the eye diagram and other parameters of the SDM channel.

5.4 Link Analysis

Each channel has independent power budget [9]. The center and outer channels pass through a short distance of free space which results in added power loss. As the outer channel has 15° incident angle, the outer channel has higher angular loss. According to equations 1.24, 1.25, and 1.26, the theoretical power budget of the center channel operating at 1550nm is presented in table 5.5. The experimental power budget for the outer channel is presented in table 5.6.
Table 5.5: Theoretical power budget of center channel with 60m carrier fiber

<table>
<thead>
<tr>
<th>Input power</th>
<th>Power after carrier fiber before collimator</th>
<th>Power after collimating lens</th>
<th>Power after focusing lens before output fiber</th>
<th>Output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2dBm</td>
<td>0.92dBm</td>
<td>0.77dBm</td>
<td>0.51dBm</td>
<td>-2.89dBm</td>
</tr>
</tbody>
</table>

Table 5.6: Experimental power budget of center channel with 60m carrier fiber

<table>
<thead>
<tr>
<th>Input power</th>
<th>Power after carrier fiber before collimator</th>
<th>Power after collimating lens</th>
<th>Power after focusing lens before output fiber</th>
<th>Output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2dBm</td>
<td>0.31dBm</td>
<td>-2.31dBm</td>
<td>-3.24dBm</td>
<td>-10.21dBm</td>
</tr>
</tbody>
</table>

The theoretical and experimental power budget of outer channel operating at 1550nm wavelength is shown in table 5.7 and table 5.8.

Table 5.7: Theoretical power budget of outer channel with 60m carrier fiber

<table>
<thead>
<tr>
<th>Input power</th>
<th>Power after carrier fiber before collimator</th>
<th>Power after collimating lens</th>
<th>Power after focusing lens before output fiber</th>
<th>Output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8dBm</td>
<td>-1.34dBm</td>
<td>-1.49dBm</td>
<td>-1.93dBm</td>
<td>-6.89dBm</td>
</tr>
</tbody>
</table>

Table 5.8: Experimental power budget of outer channel with 60m carrier fiber

<table>
<thead>
<tr>
<th>Input power</th>
<th>Power after carrier fiber before collimator</th>
<th>Power after collimating lens</th>
<th>Power after focusing lens before output fiber</th>
<th>Output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8dBm</td>
<td>-2.4dBm</td>
<td>-4.37dBm</td>
<td>-6.77dBm</td>
<td>-13.04dBm</td>
</tr>
</tbody>
</table>
Similar link analyses for center and outer channel of SDM with 150m carrier fiber is presented in tables 5.9 to 5.12.

Table 5.9: Theoretical power budget of center channel with 150m link

<table>
<thead>
<tr>
<th>Input power</th>
<th>Power after carrier fiber before collimator</th>
<th>Power after collimating lens</th>
<th>Power after focusing lens before output fiber</th>
<th>Output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2dBm</td>
<td>0.88dBm</td>
<td>0.65dBm</td>
<td>0.41dBm</td>
<td>-3.77dBm</td>
</tr>
</tbody>
</table>

Table 5.10: Experimental power budget of center channel with 150m link

<table>
<thead>
<tr>
<th>Input power</th>
<th>Power after carrier fiber before collimator</th>
<th>Power after collimating lens</th>
<th>Power after focusing lens before output fiber</th>
<th>Output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2dBm</td>
<td>-0.17dBm</td>
<td>-3.74dBm</td>
<td>-4.66dBm</td>
<td>-11.03dBm</td>
</tr>
</tbody>
</table>

Table 5.11: Theoretical power budget of outer channel with 150m link

<table>
<thead>
<tr>
<th>Input power</th>
<th>Power after carrier fiber before collimator</th>
<th>Power after collimating lens</th>
<th>Power after focusing lens before output fiber</th>
<th>Output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8dBm</td>
<td>-2.31dBm</td>
<td>-3.02dBm</td>
<td>-3.98dBm</td>
<td>-8.34dBm</td>
</tr>
</tbody>
</table>

Table 5.12: Experimental power budget of outer channel with 150m link

<table>
<thead>
<tr>
<th>Input power</th>
<th>Power after carrier fiber before collimator</th>
<th>Power after collimating lens</th>
<th>Power after focusing lens before output fiber</th>
<th>Output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8dBm</td>
<td>-2.67dBm</td>
<td>-5.12dBm</td>
<td>-7.23dBm</td>
<td>-15.29dBm</td>
</tr>
</tbody>
</table>
5.5 System Testing and Analysis

The two channel SDM optical fiber system follows a process outlined in figure 5.12 and table 5.13 to verify the quality of system. It presents LAN based system operating in C-band (1530nm to 1565nm). System performance and parameters will be tested for three different length of carrier fiber, 5 meters, 60 meters and 150 meters primarily using the eye diagram obtained with the help of a DCA. The system is operated at two different data rates (5 Gbps and 10 Gbps) at a certain length of carrier fiber to measure, analyze and calculate the SNR and BER of system. In addition, the performance of each channel working at different wavelengths of the C-band need to be tested to explore the capability of a hybrid architecture that can combine SDM with WDM. Finally, the system verifies presence or absence of discernible interference or crosstalk between the two channels.

Figure 5.12: Two channel SDM system evaluation process
Table 5.13: The variable parameters in the testing system

<table>
<thead>
<tr>
<th>$\lambda_1$</th>
<th>1561.83nm</th>
<th><strong>Data rate #1</strong></th>
<th>5.49Gbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_2$</td>
<td>1552.52nm</td>
<td><strong>Data rate #2</strong></td>
<td>11.05Gbps</td>
</tr>
<tr>
<td>$\lambda_3$</td>
<td>1546.22nm</td>
<td><strong>Length of link #1</strong></td>
<td>5m</td>
</tr>
<tr>
<td>$\lambda_4$</td>
<td>1537.26nm</td>
<td><strong>Length of link #2</strong></td>
<td>60m</td>
</tr>
<tr>
<td>$\lambda_5$</td>
<td>1529.55nm</td>
<td><strong>Length of link #3</strong></td>
<td>150m</td>
</tr>
</tbody>
</table>

The BER of the signal can be determined using

$$BER = \frac{1}{2} \left\{ 1 - \text{erf} \left( \frac{V}{\sqrt{2} \sigma} \right) \right\} = \frac{1}{2} \left\{ 1 - \text{erf} \left( \frac{Q}{\sqrt{2}} \right) \right\} \quad (5.2)$$

Where $V = \frac{1}{2} V_{th}$, $V_{th}$ is the threshold voltage. $\sigma$ is rms noise [6]. According to Eye height equation, $\sigma$ is given by

$$\text{Eye height} = (\text{one level} - 3\sigma) - (\text{zero level} + 3\sigma) \quad (5.3)$$

$$\sigma = \frac{(\text{one level} - \text{zero level})}{6 \times \text{eye height}} \quad (5.4)$$

Figure 5.13 shows the eye diagram of the center channel and outer channel with a data rate of 11.05Gbps operating at 1561.83nm and running in a carrier fiber of 5 meters. The SNR, BER and other communication parameters of center and outer channel are presented in table 5.14.
Figure 5.13: The eye diagram and data rate of 11Gbps for center channel and outer channel for a 5 meters long carrier fiber.
Table 5.14: The parameters for two channels at 11Gbps in a 5 meters link

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th>Outer</th>
<th>Center</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>11.27</td>
<td>4.20</td>
<td>Data rate</td>
<td>11 Gbps</td>
</tr>
<tr>
<td>BER</td>
<td>9.8e-10</td>
<td>6.7e-05</td>
<td>Eye height</td>
<td>43.8 μW</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>10.29 dB</td>
<td>7.73 dB</td>
<td>Eye amplitude</td>
<td>58.5 μW</td>
</tr>
<tr>
<td>Jitter RMS</td>
<td>3.29 ps</td>
<td>6.4 ps</td>
<td>Eye width</td>
<td>72.0 ps</td>
</tr>
</tbody>
</table>

Figure 5.14 shows the eye diagram of the center channel and outer channels for data rate of 5.49Gbps operating at 1561.83nm over a 5 meter long carrier fiber. The SNR, BER and other communication parameters for center and outer channel are presented in table 5.15.
Figure 5.14: The eye diagram and data rate of 5Gbps for center channel and outer channel for a 5 meters long carrier fiber.

Table 5.15: The parameters of two channels with 5Gbps in a 5 meters link

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th>Outer</th>
<th>Center</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>13.47</td>
<td>7.46</td>
<td>Data rate</td>
<td>5.49 Gbps</td>
</tr>
<tr>
<td>BER</td>
<td>4.9e-13</td>
<td>4.1e-07</td>
<td>Eye height</td>
<td>41.8 µW</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>12.7 dB</td>
<td>13.85 dB</td>
<td>Eye amplitude</td>
<td>52.5 µW</td>
</tr>
<tr>
<td>Jitter RMS</td>
<td>3.03 ps</td>
<td>6.56 ps</td>
<td>Eye width</td>
<td>162.1 ps</td>
</tr>
</tbody>
</table>

Figure 5.15 shows the eye diagram of the center and outer channels with a data rate of 5.49Gbps operating at 1561.83nm and running over a 60 meters long carrier fiber. The SNR, BER and other communication parameters for center and outer channel are presented in table 5.16.
Figure 5.15: The eye diagram and data rate at 5Gbps for center and outer channels in a 60 meters long carrier fiber
Table 5.16: The parameters for two channels at 5Gbps over a 60 meters long link

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th>Outer</th>
<th></th>
<th>Center</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SNR</strong></td>
<td>11.05</td>
<td>7.34</td>
<td><strong>Data rate</strong></td>
<td>5.49 Gbps</td>
<td>5.49 Gbps</td>
</tr>
<tr>
<td><strong>BER</strong></td>
<td>1.3e-10</td>
<td>3.8e-07</td>
<td><strong>Eye height</strong></td>
<td>37.5 µW</td>
<td>18.3 µW</td>
</tr>
<tr>
<td><strong>Extinction Ratio</strong></td>
<td>12.58 dB</td>
<td>14.99 dB</td>
<td><strong>Eye amplitude</strong></td>
<td>51.3 µW</td>
<td>30.5 µW</td>
</tr>
<tr>
<td><strong>Jitter RMS</strong></td>
<td>3.81 ps</td>
<td>6.4 ps</td>
<td><strong>Eye width</strong></td>
<td>162.1 ps</td>
<td>144.9 ps</td>
</tr>
</tbody>
</table>

Figure 5.16 shows the eye diagram of the center channel and outer channel at a data rate of 11.05Gbps operating at 1561.83nm and running over a 60 meters long carrier fiber. The SNR, BER and other communication parameters for center and outer channel are presented in table 5.17.
Figure 5.16: The eye diagram and data rate at 11Gbps for center and outer channels in a 60 meters long carrier fiber.
Table 5.17: The parameters of two channels with 11Gbps in a 60 meters long link

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th>Outer</th>
<th></th>
<th>Center</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>10.5</td>
<td>4.17</td>
<td>Data rate</td>
<td>11 Gbps</td>
<td>11 Gbps</td>
</tr>
<tr>
<td>BER</td>
<td>5.1e-09</td>
<td>6.3e-05</td>
<td>Eye height</td>
<td>31.2 μW</td>
<td>11 μW</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>10.77 dB</td>
<td>8.21 dB</td>
<td>Eye amplitude</td>
<td>46.9 μW</td>
<td>23.7 μW</td>
</tr>
<tr>
<td>Jitter RMS</td>
<td>3.33 ps</td>
<td>6.52 ps</td>
<td>Eye width</td>
<td>71.1 ps</td>
<td>49 ps</td>
</tr>
</tbody>
</table>

Figure 5.17 shows the eye diagram of the center channel and outer channel with a data rate of 11.05Gbps operating at 1561.83nm and running over a 150 meters long carrier fiber. The SNR, BER and other communication parameters for center and outer channel are presented in table 5.18.
Figure 5.17: The eye diagram and data rate at 11Gbps for center and outer channels over a 150 meters long carrier fiber

Table 5.18: The parameters of two channels at 11Gbps in a 150 meters long link

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th>Outer</th>
<th></th>
<th>Center</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>8.99</td>
<td>3.88</td>
<td>Data rate</td>
<td>11 Gbps</td>
<td>11 Gbps</td>
</tr>
<tr>
<td>BER</td>
<td>2.3e-08</td>
<td>3.6e-04</td>
<td>Eye height</td>
<td>26.9 μW</td>
<td>10.2 μW</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>8.35 dB</td>
<td>6.49 dB</td>
<td>Eye amplitude</td>
<td>41.7 μW</td>
<td>24.2 μW</td>
</tr>
<tr>
<td>Jitter RMS</td>
<td>3.8 ps</td>
<td>7.12 ps</td>
<td>Eye width</td>
<td>67.9 ps</td>
<td>51.4 ps</td>
</tr>
</tbody>
</table>

According to the analysis of the above data, short-distance, low-speed SDM system has a better performance and superior communication quality. Also, the signal quality of the center channel is better than the outer channel, as the outer channel has
more loss in the BCM and BSM stages and slightly longer optical path in carrier fiber. In general, the longer communication distance does not affect the signal quality too much. It can prove that the SDM system is suitable for LAN networks even if the communication distance increases to a kilometer or higher. On the other hand, the eye diagram is very sensitive to high data rates. The higher the speed, the stricter requirements for each component of the SDM system. Better quality electrical input signals using better RF cables and improved optical alignment can significantly improve the SDM system performance.

Using the pattern lock function on DCA, a piece of bit patterns of center channel and outer channel are restored as shown in 5.18.

![Figure 5.18: The bit pattern of center and outer channel restored by DCA](image-url)
The following charts show that the two channel SDM system works over the entire C-band for different length of carrier fiber (60m and 150m).

Table 5.19: The output power for center and outer channels operating at C-band with 60 meters long carrier fiber

Table 5.20: The BER of center and outer channels operating at C-band with 60 meters long carrier fiber
Table 5.21: Extinction Ratio for center and outer channels operating at C-band with 60 meters long carrier fiber

![Extinction Ratio of Center Channel at C Band](image1)

![Extinction Ratio of Outer Channel at C Band](image2)

Table 5.22: The output power of center and outer channels operating at C-band with 150 meters long carrier fiber

![Power of Center Channel Operating at C Band](image3)

![Power of Outer Channel Operating at C Band](image4)
Table 5.23: The BER for center and outer channels operating at C-band with 150 meters long carrier fiber

![BER of Center Channel at C Band](image1)

![BER of Outer Channel at C Band](image2)

Table 5.24: Extinction Ratio for center and outer channels operating at C-band with 150 meters long carrier fiber

![Extinction Ratio of Outer Channel at C Band](image3)

![Extinction Ratio of Outer Channel at C Band](image4)
Figure 5.19 shows the eye diagram of the center channel and outer channel with a data rate of 10.3Gbps both operating at 1561.83nm and running in a 60 meters long carrier fiber. The wavelength, BER and other communication parameters for center and outer channel are presented in table 5.25.

Figure 5.19: The eye diagram and data rate of 11Gbps for center and outer channels working at the same wavelength, 1561.83nm.
Table 5.25: The parameters for two channels with 11Gbps in a 60 meters long link operating at the same wavelength (1561nm)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Center</th>
<th>Outer</th>
<th>Center</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>10.5</td>
<td>4.18</td>
<td>11 Gbps</td>
<td>11 Gbps</td>
</tr>
<tr>
<td>BER</td>
<td>5.1e-09</td>
<td>6.5e-05</td>
<td>1561.83nm</td>
<td>1561.83nm</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>10.77dB</td>
<td>8.21 dB</td>
<td>46.9 µW</td>
<td>23.7 µW</td>
</tr>
<tr>
<td>Jitter RMS</td>
<td>3.33 ps</td>
<td>6.52 ps</td>
<td>71.1 ps</td>
<td>49 ps</td>
</tr>
</tbody>
</table>

Figure 5.20 shows the eye diagram for the center and outer channels with a data rate of 10.3Gbps operating at different wavelength (1552.52nm and 1536.22nm) and running over a carrier fiber that is 60 meters long. The wavelength, BER and other communication parameters for center and outer channel are presented in table 5.26.
Figure 5.20: The eye diagram and data rate of 11Gbps for center and outer channels working at different wavelength (1552.52nm and 1536.22nm)

Table 5.26: The parameters of two channels with 11Gbps in a 60 meters long link at different wavelength (1552.52nm and 1536.22nm)

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th>Outer</th>
<th></th>
<th>Center</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>9.75</td>
<td>4.12</td>
<td>Data rate</td>
<td>11 Gbps</td>
<td>11 Gbps</td>
</tr>
<tr>
<td>BER</td>
<td>4.2e-09</td>
<td>5.9e-05</td>
<td>Wavelength</td>
<td>1552.52nm</td>
<td>1536.22nm</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>10.35dB</td>
<td>7.21 dB</td>
<td>Eye amplitude</td>
<td>45 µW</td>
<td>21.03 µW</td>
</tr>
<tr>
<td>Jitter RMS</td>
<td>3.31 ps</td>
<td>6.02 ps</td>
<td>Eye width</td>
<td>61 ps</td>
<td>52 ps</td>
</tr>
</tbody>
</table>

Figure 5.21 shows the eye diagram of the center and outer channels with a data rate of 10.3Gbps and both channels operating at the same wavelength at the edge of C-band (1529.55nm) and running over a carrier fiber that is 60 meters long. The wavelength, BER and other important parameters for center and outer channels are presented in table 5.27.
Figure 5.21: The eye diagram and data rate of 11Gbps for center and outer channels both working at the same wavelength 1529.55nm
Table 5.27: The parameters of two channels with 11Gbps over a 60 meters long link at the same wavelength (1529nm)

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th>Outer</th>
<th></th>
<th>Center</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SNR</strong></td>
<td>11.19</td>
<td>4.20</td>
<td><strong>Data rate</strong></td>
<td>11 Gbps</td>
<td>11 Gbps</td>
</tr>
<tr>
<td><strong>BER</strong></td>
<td>9.8e-09</td>
<td>6.7e-05</td>
<td><strong>Wavelength</strong></td>
<td>1529.55nm</td>
<td>1529.55nm</td>
</tr>
<tr>
<td><strong>Extinction Ratio</strong></td>
<td>9.8dB</td>
<td>7.86 dB</td>
<td><strong>Eye amplitude</strong></td>
<td>44.3 μW</td>
<td>27.1 μW</td>
</tr>
<tr>
<td><strong>Jitter RMS</strong></td>
<td>3.09 ps</td>
<td>6.12 ps</td>
<td><strong>Eye width</strong></td>
<td>66 ps</td>
<td>32.5 ps</td>
</tr>
</tbody>
</table>

According to the experimental data, there is no crosstalk between SDM channels, and two channels are completely independent, irrespective of their operating wavelengths. Utilizing the independence of the SDM channel, the optical fiber communication system based on SDM can complement other multiplexing technologies to form a hybrid architecture combining systems such as wavelength division multiplexing (WDM) or orbital angular momentum of photon based multiplexing (OAMM), etc. and can lead to hybrid optical communications architectures that support data rates exceeding Multi-Tbps.
5.6 Conclusion

Spatial domain multiplexing (SDM) is a novel technology that allow spatial reuse the optical frequency in optical fiber communication. Multi-channel SDM channels can simultaneously propagate with same wavelength or different wavelength over a single multi-mode carrier fiber.

In order to obtain the maximum coupling efficiency and clear SDM output patterns, several approaches for the different SDM components are designed and evaluated. For the BCM, bare fiber covering fiber tube, optical waveguide, and integrated module using 3D printing technology etc. were evaluated and tested. Similarly, optical-to-electrical and optical-to-optical schemes for BSM were proposed and evaluated. Mirror with elliptical hole can effectively separates the SDM channel without crosstalk, and then directs each channel to the output fiber in a reasonable fashion.

The combination of BCM, BSM, and carrier fiber forms a complete SDM optical fiber communication system. A system combining all three was designed, built and analyzed using the simulation and experimental tools. The experimental system used TXFP transceivers to transmit two SDM channel of same wavelength at 10Gb/s simultaneously over a single carrier fiber. The DCA was used to analyze the experimental system using measured and calculated parameters such as the eye diagram and BER for each channel and the power budget and communication performance over the entire C-band was measured, tested and analyzed.

In short simulated and experimental results are presented to successfully prove the operation of a two channel SDM optical fiber communication system, that operate at exactly the same or differing wavelengths, to simultaneously transmit two channels at data rate of 10Gb/s in the C-band for the LAN applications.
5.7 Future Work

- Four channel SDM communication system based on de-multiplexing with a combination of mirrors with elliptical hole.
- A Multi-Tb/s SDM communication system can be implemented using O-band and C-band.
- The development of SDM specific simulation system to enable comprehensive simulation and modeling using tools similar to Zemax and OptiSystem.
- New design of BCM and BSM based on photonic integrated circuit (PIC) to maximize the coupling efficiency maximum efficiency and ideally package the whole SDM system over a semiconductor chip.
Reference


