Novel Optical Fibers for High-Capacity Transmission System

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ABSTRACT

The rapid growth of multi-media and data rich applications has driven the bandwidth demand for long-haul fiber-optic links at unprecedented rates. At the same time, growing capacity demands also imposes challenges on bandwidth and interconnects in data centers. Optical fibers are continuing improving their performance to meet the bandwidth demand in both long haul and short reach applications. While continuing improvements in conventional fiber optic technologies will increase the system capacity further in a short term, recent studies show that the transmission capacity over single-mode optical fibers is rapidly approaching its fundamental Shannon limit. To overcome this limit, new technologies using space division multiplexing are needed to provide a solution to the future capacity growth.

In this paper, we discuss novel optical fibers for increasing capacity for transmission systems. For conventional fibers for long haul transmission, because transmission impairments such as chromatic dispersion, polarization-mode dispersion can be perfectly compensated for by digital signal processing, the only fiber parameters that can be optimized further are fiber attenuation and effective area. We will discuss system figure of merit for the two parameters and present recent results on ultra-low loss and large effective area fibers. For short reach applications, we will review the current efforts in improving multimode fiber bandwidth and discuss new trends in multimode fibers to meet future bandwidth demand. For next generation fibers, we will focus on multicore and few mode fibers for space division multiplexing, which has the potential to increase the capacity by an order of magnitude. We will present fiber design considerations and review recent progress on multicore and few mode fibers. Finally, we will discuss major challenges in space division multiplexing applications using multicore and few mode fibers.

KEY WORDS

ultra-low loss fiber, large effective area fiber, space division multiplexing, multicore fiber, few mode fiber

I. Introduction

Since the first demonstration of optical fiber of less than 20 dB/km in 1970 [1], optical fibers and transmission systems have evolved rapidly during the past more than four decades. The advances of fiber, component and system technologies have increased the transmission capacity tremendously. Historic data show that the transmission capacity of a single fiber has increased by a factor of approximately 10 every four years [2].

The long haul transmission system has gone through four generations. The first generation of optical fiber communication system utilized multimode optical fibers and LED sources operated in the 850 nm wavelength region [3]. The advantage of the multimode fiber is that it has a large core and high numerical aperture; therefore, coupling of the light from the source into the fiber, splicing and connectorization are not difficult. However, the multimode fiber has a fundamental bandwidth limitation due to intermodal dispersion.

One approach to eliminate intermodal dispersion is to utilize a single-mode optical fiber instead of a multimode optical fiber. With the development of semiconductor lasers [4,5] and the opening of long wavelength transmission windows [6,7] as well as the advance in single-mode fiber splicing technology [8,9] in the later 1970s, single-mode fiber transmission systems became possible. The second generation of optical fiber communication system employed standard single mode fiber and single mode lasers at 1310 nm. When the attenuation of optical fiber is considered, the attenuation in the 1310 nm wavelength region is less than that in 850 nm. In addition, a standard single-mode fiber exhibits nearly zero dispersion in this wavelength region [10-14].

The attenuation of a single-mode optical fiber is the lowest in the 1550 nm wavelength window. However, the chromatic dispersion of a standard single-mode fiber in this wavelength window is very large (+17 ps/km/nm), which
was a limitation for high data rate systems. In order to take the advantage of lowest attenuation at this wavelength window, a new type of fiber, known as a dispersion-shifted optical fiber (DSF) whose chromatic dispersion is minimum at the 1550 nm wavelength region was developed [15-21]. This in effect allows the use of conventional lasers exhibiting relatively large spectral width of several nm, which enabled the third generation optical fiber transmission system at 1550 nm.

The dispersion shifted fiber was optimized for single channel transmission at 1550 nm. Before it was widely deployed in actual telecommunication systems in the late 1980s, new advances in erbium doped amplifiers (EDFA) [22,23] and wavelength-division multiplexing (WDM) [24] technology made the multiple channel transmission viable for the fourth generation high capacity optical fiber transmission system. It was found soon that the dispersion shifted fiber with dispersion value of around zero at 1550 nm was not suitable for WDM transmission [25]. This is because the nonlinear effect of four-wave mixing is the strongest when the dispersion is zero [26], which causes significant crosstalk between two neighboring channels. To reduce the four-wave mixing effect, it is advantageous to have a certain amount of dispersion. On the other hand, the dispersion should be small to minimize the dispersion penalty. Therefore the concept of non-zero dispersion-shifted fiber (NZDSF) was proposed [27-30]. Typical dispersion value for NZDSFs is in the range of 3-8 ps/nm/km at 1550 nm with an effective area of about 50 µm². Because the nonlinear effects are inversely proportional to the effective area of fiber, increasing the effective area will reduce further the nonlinear effects. To increase the effective area, profiles designs with large effective area of about 72 µm² were developed [31-34]. NZDSFs have been widely deployed worldwide for high capacity WDM networks.

The WDM technique has opened a new dimension to increase the transmission capacity by increasing the number of wavelength channels. In parallel to the WDM development, the channel rate has improved to meet the increasing bandwidth demand. The channel rate has increased from 2.5 Gb/s to 10 Gb/s and then to 40 Gb/s using intensity modulation and direct detection. With the continuous increase in channel rate, coherent technologies have attracted a large interest over the recent years [35]. Coherent detection allows information to be encoded with two degrees of freedom, which increases the amount of information per channel. It also allows integrating digital signal processing (DSP) function into a coherent receiver to make a digital receiver. With coherent detection techniques, advanced modulation formats [36] such as BPSK, QPSK, 8PSK, 16QAM and higher levels of modulation formats have been proposed, which have pushed the channel capacity to beyond 100 Gb/s. Coherent detection in conjunction with DSP can handle transmission impairments from chromatic dispersion and polarization mode dispersion. This new system technology has changed the fiber design direction towards fibers with lower loss and larger effective area to deal with nonlinear transmission impairments.

While continuing improvements in conventional fiber optic technologies will increase the system capacity further in a short term, recent studies show that the transmission capacity over single-mode optical fibers is rapidly approaching its fundamental Shannon limit [37]. To overcome this limit, new technologies using space division multiplexing (SDM) are needed to provide a solution to the future capacity growth [2]. There are two approaches for space division multiplexing, one is to use multicore fiber (MCF) and the other is to use few-mode fiber (FMF). SDM adds a new dimension to the fiber transmission system, which has the potential to increase the capacity by an order of magnitude. MCF and FMF for SDM are current hot topics in optical fiber research.

Although multimode fiber (MMF) was replaced by single-mode fiber for long haul applications [38], MMF is still the fiber of choice for short distance data network applications because it offers efficient coupling from light sources, low cost splices and connectors between fibers. In the last 10 years, MMF and short-wavelength 850 nm VCSELs have emerged as dominant technologies for short-reach high data rate networks [39, 40]. MMF is used in local area networks (LAN) and data centers where data rates are higher or reach lengths are longer than can be met with copper networks, and the use of VCSELs makes the overall system cost effective to enable widespread adoption. The fast growth is driven by the demand for higher data rates for computer connections, data storage, and local communication including linking to internet traffic. Server virtualization, cloud computing, and higher speed ports are now driving networks to 40/100 Gb/s and eventually higher speeds (400Gb/s) in data centers. To meet higher data rate and longer distance demands, MMF has been evolving to improve its bandwidth capability and performance.

In this paper, we review recent progress on novel optical fibers for increasing capacity for both long haul and short length transmission systems. We discuss first ultra-low loss and large effective area fibers for applications in high capacity long-haul WDM systems. Then we will review new developments in MMF for high capacity short reach applications. Finally we will discuss new emerging MCF and FMF for increasing the fiber capacity using SDM technology.

II. Ultralow loss and large effective area fiber for long haul systems
With the new developments in coherent detection and digital signal processing technologies, transmission impairments from fiber dispersion effects are no longer an issue. This simplifies greatly the fiber design. The only important fiber parameters for high capacity long-haul transmission are the fiber attenuation and effective area.

The total attenuation of an optical fiber is the addition of intrinsic loss factors such as Rayleigh scattering $\alpha_{RS}$, infrared absorption $\alpha_{IR}$ and ultraviolet absorption $\alpha_{UV}$, and extrinsic loss factors such as absorption due to transition metals $\alpha_{TM}$, absorption due OH ions $\alpha_{OH}$, scattering due to waveguide imperfections $\alpha_{IM}$ and loss due to fiber bending effects $\alpha_{BL}$:

$$\alpha = \alpha_{RS} + \alpha_{IR} + \alpha_{UV} + \alpha_{TM} + \alpha_{OH} + \alpha_{IM} + \alpha_{BL}$$

The contaminants due to transition metals can be eliminated practically in the fiber preform manufacturing processes by using chemical vapor deposition techniques with high pure chemical raw materials. The OH concentration can be reduced to minimum level using chlorine drying. Waveguide imperfection loss is caused by the geometry fluctuation at the core and cladding boundary. The boundary fluctuation is mainly due to the residual stress which is induced during the manufacturing process. The residual stress depends on the magnitude of the viscosity difference between the core and cladding and the fiber drawing tension. The stress can be reduced by matching the viscosity of the core and cladding [41]. For the intrinsic factors, the most important one is the Rayleigh scattering loss. The Rayleigh scattering loss can be expressed by the sum of two contributions from density and concentration fluctuations [42]:

$$\alpha_{RS} = \alpha_\rho + \alpha_c$$

The density fluctuation to the scattering coefficient depends on the fictive temperature, $T_f$, which is determined as the temperature where the glass structure is the same as that of the supercooled liquid:

$$\alpha_\rho = \frac{8\pi^3}{3\lambda} n^2 p^2 \beta_T k_B T_f$$

where $\lambda$ is the wavelength of incident light, $p$ the photoelastic coefficient, $n$ the refractive index, $k_B$ the Boltzmann constant, $\beta_T$ the isothermal compressibility. The concentration fluctuation is proportional to:

$$\alpha_c \sim \left(\frac{\partial n}{\partial C}\right)^2 \langle \Delta C^2 \rangle T_f$$

Because the Rayleigh scattering is mainly caused by frozen-in density fluctuation, and is proportional to the fictive temperature, $T_f$. Therefore, it is necessary for suppressing the Rayleigh scattering to reduce $T_f$ as much as possible to increase structural relaxation. To reduce the concentration fluctuation, it is advantageous to reduce GeO$_2$ dopant level in the core because the Rayleigh scattering loss is proportional the GeO$_2$ concentration. For this reason, it is better to use pure silica material in the core [43, 44].

The fiber macro- and micro-bending losses are important factors for fiber attenuation, especially for fibers with large effective areas. To increase the effective area while keeping good bending performance, the core refractive index profile needs to be carefully designed. The optical properties that need to be considered include the effective area, cable cutoff wavelength and bending losses. Fig. 1 shows three profile designs that can be used for low loss and large effective area fibers. The relationship between these attributes can be understood by considering a simple step index design, which is shown schematically in Fig. 1(a). A step index profile is characterized by two parameters: the relative refractive index change or the core delta and the core radius. To increase the effective area, the core radius needs to be increased but core delta needs to be reduced to keep the cable cutoff wavelength below the minimum wavelength of the application window, e.g. 1530 nm for 1550 nm window. Due to the cable cutoff wavelength limitation, the bending losses will increase when the effective area gets larger. The macrobend loss usually has a specified upper limit, e.g. less than 0.5 dB for 100 turns at a bend diameter of 60 mm for practical applications. For a step index design, with the cable cutoff and macrobend loss constraints, the maximum effective area that can be achieved is approximately $110 \, \mu m^2$. 

\[\begin{array}{ccc}
(a) & (b) & (c)
\end{array}\]
To increase further the effective area, we can add a depressed cladding layer or a low index trench as shown in Fig. 1(b) and (c) to suppress macrobending losses while keeping the cable cutoff wavelength below 1530 nm. For example, Fig. 2 shows measured bend loss as a function of effective area for design (b) at 1550 nm. For 30 mm bend diameter, the bend loss start to increase rapidly when effective area is greater than 130 µm², while for 40 mm bend diameter, the effective area can be as large as 175 µm².

![Fig. 2: Bend loss as a function of effective area for design (b).](image)

However microbending loss becomes a limiting factor for large effective area [45]. If we use the fiber-coating system currently used for standard single mode fiber (G.652), it has been reported that the effective area can only be increased to approximately 120 µm² due to microbending loss increase [46]. Microbending is an attenuation increase caused by high frequency longitudinal perturbations to the waveguide. These perturbations couple power from the guided fundamental mode in the core to higher-order cladding modes that are lost to the outer medium [47]. A phenomenological model introduced by Olshansky captures the importance of treating the glass and coating as a composite system by predicting that the microbending losses scale with

$$\gamma_{\text{micro}} \propto \frac{a^4}{b^6 \Delta^3 E^{3/2}}$$

where $a$ is the core radius, $b$ is the cladding radius, $\Delta$ is the relative refractive index of the core and $E$ is the elastic modulus of the primary coating layer that surrounds the glass. As it is mentioned earlier that core delta and core radius are determined by the effective area and the cutoff wavelength, these variables are not completely independent and together do not offer a significant lever for reducing microbending sensitivity. This leaves the inner primary modulus as a key factor for addressing the increased microbending sensitivity in large effective fibers. Making the inner primary coating softer will help cushion the glass from external perturbations and hence improve the microbending performance.

The role of the primary modulus in mitigation of microbending was demonstrated experimentally. In the experiment, fibers of different effective areas were made with two coatings which have inner primary moduli of approximately 0.43 and 0.13 (Coating A and B, respectively). Fig. 3 shows measured fiber attenuation. For effective area between 110 and 115 µm², the attenuation of fibers with the two coatings are the same. This shows that intrinsic attenuation can be realized with effective area less than 115 µm². For the effective area larger than 120 µm², the microbending loss starts to increase with Coating A, while Coating B keeps the microbending loss to nearly zero level for effective area up to 135 µm². It is evident that to derive the benefits of ultra-low attenuation, a fiber with very large effective area requires a coating with an optimized inner primary modulus to protect against microbending. It is estimated that effective area of about 150 µm² is possible with further optimization of primary coating.
The fiber effective area and attenuation affect optical signal to noise ratio (OSNR) of a transmission system. The main factors that determine the OSNR for a given system link at a given distance are the channel launch power into each span, the noise figure of the optical amplifiers, the loss per span, and the total number of spans in the link. Of these, the factors that are directly related to optical fiber parameters are channel launch power and span loss. The channel launch power is limited by optical nonlinear impairments in the fiber, which scale with the ratio of the fiber effective area $A_{\text{eff}}$ over $n_2^2$, the nonlinear index of refraction. The span loss is directly related to the fiber attenuation coefficient $\alpha$. To quantify benefits of large effective area and low loss on OSNR, a fiber figure of merit (FOM) is defined \[49\]:

$$\text{Fiber FOM (dB)} = 10\log \left( \frac{A_{\text{eff}} \cdot n_{2,\text{ref}}}{A_{\text{eff,ref}} \cdot n_{2}} \right) - (\alpha - \alpha_{\text{ref}}) \cdot L - 10\log \left( \frac{L_{\text{eff}}}{L_{\text{eff,ref}}} \right)$$ \hspace{1cm} (6)

where $A_{\text{eff}}$, $\alpha$, $n_2$, and $L_{\text{eff}}$ are the effective area, attenuation coefficient, nonlinear refractive index and effective length of the fiber under consideration, and $A_{\text{eff,ref}}$, $\alpha_{\text{ref}}$, $n_{2,\text{ref}}$, and $L_{\text{eff,ref}}$ are the effective area, attenuation coefficient, nonlinear refractive index and effective length of the reference fiber, and L is the span length.

Fig. 4 illustrates the fiber FOM as a function of effective area $A_{\text{eff}}$ and attenuation $\alpha$ for a system with 75 km span length. Red circle represents parameters of reference fiber \[49\]. The reference fiber parameters used here are for a typical standard single mode fiber with 0.2 dB/km attenuation and 80 $\mu$m$^2$ effective area. The discontinuity observed in the contour plot in Fig.4 between 0.179 dB/km and 0.178 dB/km is the result of an assumption made here that for attenuation values $\leq 0.178$ dB/km, the fiber will have to be a silica core fiber rather than a conventional Germanium-doped fiber. Fig. 4 shows clearly that increasing the fiber FOM can be attained by either increasing the fiber effective area or decreasing the fiber attenuation. In fact, for this example of 75 km span length, $>5$ dB increase in FOM can be obtained by moving to an ultra-low loss fiber with attenuation of 0.162 dB/km and an effective area of at least 145 $\mu$m$^2$. For longer spans or unrepeated long links, the ultra-low loss becomes even more important. An analysis shows that an attenuation decrease of -0.035 dB/km is equivalent to
increasing the effective area by 34, 55, and 83 μm² above the reference fiber’s 80 μm² effective area for 50, 75, and 100 km spans, respectively.

Table 1. Transmission experiments using low loss and large effective area fibers

<table>
<thead>
<tr>
<th>Fiber</th>
<th>System</th>
<th>α</th>
<th>A_eff</th>
<th>Span (km)</th>
<th>Amplifier</th>
<th>Data rate (Gb/s)</th>
<th>Modulation format</th>
<th>No of channels</th>
<th>Channel spacing (GHz)</th>
<th>Reach length (km)</th>
<th>Total capacity (Tb/s)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.163</td>
<td>76-128</td>
<td></td>
<td></td>
<td>365</td>
<td>EDFA/Raman</td>
<td>112</td>
<td>PM-QPSK</td>
<td>40</td>
<td>50</td>
<td>365</td>
<td>4</td>
<td>50</td>
</tr>
<tr>
<td>0.162</td>
<td>134</td>
<td></td>
<td></td>
<td>100</td>
<td>EDFA</td>
<td>112</td>
<td>PM-QPSK</td>
<td>16</td>
<td>50</td>
<td>7200</td>
<td>1.6</td>
<td>51</td>
</tr>
<tr>
<td>0.165</td>
<td>85,134</td>
<td></td>
<td></td>
<td>200</td>
<td>EDFA/Raman</td>
<td>112</td>
<td>PM-QPSK</td>
<td>8</td>
<td>32</td>
<td>5400</td>
<td>0.8</td>
<td>52</td>
</tr>
<tr>
<td>0.161</td>
<td>112</td>
<td></td>
<td></td>
<td>50</td>
<td>EDFA</td>
<td>112</td>
<td>PDM-QPSK</td>
<td>80</td>
<td>50</td>
<td>9000</td>
<td>8</td>
<td>53</td>
</tr>
<tr>
<td>0.160</td>
<td>112, 146</td>
<td></td>
<td></td>
<td>60.6</td>
<td>EDFA</td>
<td>120.5</td>
<td>PDM-8QAM-OFDM</td>
<td>115</td>
<td>25</td>
<td>10181</td>
<td>11.5</td>
<td>54</td>
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<tr>
<td>0.17</td>
<td>80</td>
<td></td>
<td></td>
<td>125</td>
<td>EDFA</td>
<td>112</td>
<td>PDM-QPSK</td>
<td>1</td>
<td>50</td>
<td>3000</td>
<td>0.26</td>
<td>55</td>
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<tr>
<td>0.162</td>
<td>112</td>
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<td>100</td>
<td>Raman</td>
<td>112</td>
<td>PM-QPSK</td>
<td>40</td>
<td>50</td>
<td>10200</td>
<td>4</td>
<td>49</td>
</tr>
</tbody>
</table>

The benefits of optical fibers with ultra-low loss and large effective area as quantified by the fiber FOM have been experimentally demonstrated by several recent 100 Gb/s transmission experiments [49-55]. Table 1 summarizes seven experiments. In these experiments, optical fibers used have attenuation of 0.16-0.17 dB/km, and effective area of 80 to 146 μm². The transmission system investigated in Ref. 49 is an unrepeatered system with span length 365 km. In the other experiments, the span length ranges from 50 to 200 km. Effective area management approach is used in Ref. 50 and 52 to reduce nonlinearity using a larger effective area fiber at beginning of each span and to increase Raman efficiency using a smaller effective area at the end of each span. Reach lengths from 3000 km to 10200 km are demonstrated, which can cover system link lengths for terrestrial and submarine applications. These experiments and results highlight the long reach lengths and good system performance enabled by the fiber attributes.

III. New Multimode fibers for short reach systems

The fast growing internet traffic demands for high speed transmission and storage of huge amount of information by datacenters, super computers and consumer electronics. These applications have short reach distances from a few meters to a few hundred meters, where multimode fiber (MMF) is the fiber of choice for low cost system solutions. The increased data flows demand for MMF with higher and higher bandwidth. At same time, the systems require lower bend loss multimode fibers for improving power operating margins, space savings, cooling efficiency and overall connection and cable management. In this section, we review recent new developments in MMF and discuss new trends for high data rate MMF applications [40].

III-1. High bandwidth MMF at 850 nm

MMF is designed with an alpha profile to minimize the modal group delays to achieve high bandwidth:

\[
\Delta = \Delta_0 \left[1 - \left(\frac{r}{r_0}\right)^\alpha\right]
\]

where \(r_0\) is the core radius, and \(\Delta_0\) is maximum relative refractive index change in the core:

\[
\Delta_0 = \frac{n_0^2 - n_1^2}{2n_0^2}
\]

where \(n_0\) is the refractive index in the center of the core, and \(n_1\) is the refractive index of the cladding.

When the \(\alpha\) value is properly chosen, the modal bandwidth of the MMF can be optimized at a specified wavelength [56]. Fig. 5 shows a modeled bandwidth of a 1% delta 50 μm MMF at 850 nm. For this fiber, the theoretical peak bandwidth is over 13 GHz.km. However, the bandwidth is very sensitive to the \(\alpha\) value as shown in Fig. 5. Various imperfections in the manufactured core profile limit the actual bandwidth.
As fiber manufacturing processes and designs have improved, MMF bandwidth has improved tremendously to meet new bandwidth demands. Table 1 shows different types of standard MMF. The 62.5 \( \mu \text{m} \) MMF has a higher NA and a larger core which enables more light coupled to the fiber from a LED source, which could support 2 km transmission at 10 Mb/s and even faster data rates, up to 100 Mb/s, in shorter distance applications like the “Fast Ethernet” standard of the early 1990’s. In the mid-1990s, developments of a 1 Gb/s optical Ethernet standard and the low cost VCSELs at 850 nm favored the use of 50 \( \mu \text{m} \) fiber with its lower modal dispersion and higher bandwidth due to its lower refractive index difference. The coupling to 50 \( \mu \text{m} \) fibers was no longer an issue due to the smaller spot size and lower NA of VCSELs. Therefore, 50 \( \mu \text{m} \) fibers have become the fiber of choice for 1 Gb/s and 10 Gb/s Ethernet applications. 50 \( \mu \text{m} \) MMF has evolved from OM2 (500 MHz.km) to OM3 (2000MHz.km) and now to OM4 (4700MHz.km). Further improvement in
bandwidth is theoretically possible through tighter profile control but at the higher cost of fiber manufacturing process control.

The core $\Delta_0$ also affects the maximum bandwidth that can be achieved because the bandwidth scales with $1/\Delta^2$ as shown in Fig. 6. The bandwidth is doubled when the core $\Delta_0$ is reduced from 1% to 0.75%. However, reducing the core $\Delta$ will increase the bend loss. This problem can be mitigated by reducing the core diameter and using a low index trench in the cladding as discussed in the section below.

For transmission systems using multimode VCSELs operating at 850 nm, further increasing the bandwidth of MMF beyond OM4 offers very small benefits as the system is limited by chromatic dispersion. For multimode VCSELs, some chromatic dispersion effects can be compensated by designing a MMF with slightly left tilt in differential mode delay (DMD) [57] or using a short MMF compensation jumper that has the desired DMD tilt [58]. The latter offers flexibility to adapt VCSELs with different dispersion characteristics. To take full advantages of bandwidth higher than OM4, we can use single mode 850 nm VCSELs [59] or move to the system to longer wavelengths where the chromatic dispersion is lower.

III-2. Bend-insensitive MMF

For data center applications, bend-insensitive MMF is attractive because it offers improved power operating margins, enables smaller cable, hardware and equipment designs that can deliver space savings, easier handling for frequent changes and better cooling efficiency, and better overall connection and cable management.

Fig. 7: Schematic of a bend-insensitive MMF refractive index profile

Fig. 8: Bend loss at 850 nm of standard and bend-insensitive MMF.

Fig. 7 shows a bend-insensitive MMF refractive index profile design [60]. It has an alpha graded index core with a low index trench in the cladding. The trench reduces the optical power of guided modes in the cladding region, thus improving their bend performance. The core delta and trench volume are carefully selected to balance the bend
performance and the compatibility with standard MMF. The trench’s location is also important to achieve high bandwidth by correcting delays of outer mode groups. By properly designing the core and the trench, high bandwidth OM4 MMF with low bend loss can be achieved. Fig. 8 shows measured bend loss at 850 nm for a bend-insensitive fiber compared to a standard MMF. The bend loss of the bend-insensitive MMF is more than 10 times lower than the standard MMF without the low index trench.

III-3. MMF for long wavelengths

As bandwidth reaches OM4 levels for 850 nm MMF, the chromatic dispersion becomes a limiting factor for high data rate and long reach links because of large transceiver linewidths employed with VCSELs. Single-mode fibers or restricted launches into the fundamental mode of an 850 nm MMF at a long wavelength using a single mode laser [61] have been suggested for increasing the data rate or distance; however the high alignment precision required results in high packaging costs for laser to fiber coupling, leading to higher optical transceiver costs.

One attractive solution is to use a MMF optimized for high bandwidth at a longer wavelength, for example 980 nm/1060 nm, or 1310 nm in conjunction with long wavelength sources such as long wavelength VCSELs and integrated silicon-photonic (SiPh) transceivers. The long wavelength MMF system retains the advantage of low loss coupling and passive alignment of conventional 850 nm MMF systems. At the same time, the chromatic dispersion and attenuation of the fiber are much lower at a longer wavelength. This can be seen in Fig. 9, where the chromatic dispersion and loss are plotted as a function of wavelength. At 1060 nm, both the chromatic dispersion and loss are reduced by more than 2 times, and at 1310 nm, the chromatic dispersion is nearly zero and the loss is only one fifth of that at 850 nm. The low loss and low chromatic dispersion together with the high modal bandwidth enables higher data rate and longer length transmissions. Recently, 25 Gb/s transmissions have been demonstrated through 820 nm MMF with a 1310 nm SiPh transceiver [62], and through 500 m of MMF with a 1060 nm VCSEL transceiver [63], which clearly show the advantages of long wavelength MMF transmissions.

![Fig. 9: Chromatic dispersion and loss of MMF.](image)

III-4. MMF for Consumer Applications and very short distance networks

With the increasing deployment of Fiber to the Home (FTTH), it is becoming apparent that optical communication may find new opportunities in short-reach consumer electronics interconnects or home-networking. For fiber designs, consumer interconnects represent a new application space that has different requirements from traditional applications such as in data centers. In this application space, in addition to the bandwidth requirement, the fiber must be designed to minimize the total link loss in the presence of misalignments, which allow the use of inexpensive optical components and low cost assembly processes. The deployment conditions require the fiber for even lower bend loss, and high mechanical reliability under small-radius bend conditions.
To increase tolerance to misalignments, it is beneficial to increase the core diameter and NA of the fiber. A comprehensive analysis was performed for a high-speed link operating at 10 Gb/s [64] using an 850 nm VCSEL. The result is shown in Fig. 10. A marked improvement of link loss occurs when the NA increases up to ~0.3 and the core diameter increases up to ~80 µm. Further increase in the core diameter or NA provide only a marginal advantage because the coupling improvements at the transmitter and in-line connectors become marginally better, while at the same time the coupling degradation when focusing the light onto the photodiode increases. The total link loss is approximately 6.2 dB for a fiber with 80 µm core diameter and NA=0.3, compared to 11.5 dB for a standard MMF with 50 µm core diameter and NA=0.2.

To make a fiber to withstand consumer handling, particularly in transient short term tight bend conditions of about 3 mm diameter, a fiber design with smaller glass diameter reduces the applied stress in bend and can increase the lifetime by several orders of magnitude. Studies show that at 3 mm bend diameter, the lifetime is increased by approximately 4 orders of magnitude for a 100 µm glass fiber compared a fiber with 125 µm glass diameter.

The need for high data transfer rates requires the fiber to have a graded index core, since a step index core cannot achieve sufficiently high bandwidth and support >10 Gb/s over relatively long distances. The addition of a low index trench in the cladding is beneficial for achieving both high bandwidth and low bend performance as discussed in Sec. III-2. By using a core delta of 2% with a low-index trench, bend loss on the order of 1 dB in a 3 mm bend diameter was achieved. Transmissions at 10 Gb/s on a 50 m link with less than 1 dB power penalty were demonstrated [64].

IV. Fibers for space division multiplexing systems
Space division multiplexing is a promising approach for future capacity growth. However, the conventional single mode or multimode fibers are not suitable for this application. New fibers such as multicore fiber and the other is few-mode fiber need to be developed. In this section, we discuss the two types of fiber and review recent progress in space division multiplexing using these fibers.

IV-1. Few mode fibers
Mode-division multiplexing (MDM) in a multimode fiber is not a new concept. The potential of using different modes to carry independent channels was recognized at early days of fiber optics. MDM was first demonstrated over a short distance of 10-m using a conventional multimode fiber, in which the distance was limited by mode coupling [65]. The success of multiple-input-multiple-output (MIMO) systems in wireless communications has motivated interesting investigations of MIMO in optical fiber communications [66]. MIMO technology can deal with the mode coupling issue, increasing the transmission distance and capacity but requires more complex decoding techniques and digital signal processing power. Conventional MMF with 1% core delta and 50 µm core diameter has more than 100 modes, which requires very high complex DSP for long haul transmission. So far, the research efforts have been focused on few mode fiber (FMF) transmission systems. For FMF transmission, it is desirable to minimize differential mode group delay (DMGD) in order to reduce decoding complexity. It is also advantageous to have large effective areas to reduce the nonlinear effects.
Fig. 11 shows profile designs of FMF. Fig. 11(a) is a step index design and Fig. 11(b) is a graded index design. Both designs can be described by the $\alpha$ profile function described by Eq. (7). For a step index profile, the $\alpha$ value approaches infinity. The step index design is simple. The number of modes is determined by the core $\Delta_0$ and the core radius $r_0$. However, it is impossible to design a fiber with low DMGD over a transmission band like C and L bands. The graded index profile has shape factor $\alpha$, which adds one more degree of freedom. By controlling the $\alpha$ value, low DMGD can be realized [67]. To improve the fiber bending performance, a low index trench can be added in the cladding as shown in Fig. 11(c). The low index trench does not only reduce the fiber bending loss, but also reduces the mode delay of the outer mode group if the location of trench is optimized, similarly to the bend insensitive MMF described in Ref. [60].

With graded index profile designs, very low DMGD can be obtained theoretically. Fig. 12 shows the root mean square (RMS) DMGD for optimum alpha profiles designs with different delta values. It can be seen that DMGD is less than 10 ps/km in the whole C+L WDM window. As an example, fiber properties of a low DMGD profile design (Fiber 0) are listed in in Table 1. In this example, the DMGD is lower than 1 ps/km for a wavelength window between 1500 and 1600 nm. DMGDs as low as 50 ps/km have been achieved for 3-LP mode fibers [69, 70]. Fibers with 6-LP modes and DMGD less than 85 ps/km have been reported [71, 72].

In addition to the very low delay, Table 1 shows also that the effective areas of the LP_{01} and LP_{11} are both very large. The Effective area of LP_{01} mod is 177 $\mu$m$^2$ and the effective area of LP_{11} mode is 238 $\mu$m$^2$. Although the effective areas are much larger than single mode fibers, the bending performance is good enough for practical cable applications because the cutoff of the LP_{11} mode is around 4 $\mu$m. The large effective areas are suitable for reducing nonlinear effects for long haul transmission.
Another way to realize low DMGD in a FMF link is to use a DMGD managed approach as shown in Fig. 13, where FMF segments with positive and negative DMGD are concatenated to form a span with an ultra-low cumulative DMGD [68, 73]. Positive and negative DMGD can be designed by changing the $\alpha$ value in a graded index profile design.

Fig. 14 shows differential mode delays as a function of wavelength for two fiber designs. Table 2 shows optical properties of the two fibers (Fibers 1 and 2). The two fibers have opposite delays and delay slopes. By choosing the fiber length ratio of 1.2:1 for the two fibers, a fiber link with nearly zero delay can be constructed. For example, the net delay obtained by combining 552 km of Fiber 1 with 460 km of Fiber 2 is plotted in Fig. 3. The net delay of the ~1000 km fiber link is less than 0.5 ps/km over the entire wavelength range between 1.5 to 1.6 $\mu$m.

![Fig. 14. Fiber design examples with positive and negative DMGD.](image)

**Table 2. Optical properties of fiber design examples**

<table>
<thead>
<tr>
<th>Fiber</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP$_{01}$ MFD at 1550 nm ($\mu$m)</td>
<td>15.0</td>
<td>15.3</td>
<td>14.7</td>
</tr>
<tr>
<td>LP$_{01}$ Effective Area at 1550 nm ($\mu$m$^2$)</td>
<td>177</td>
<td>186</td>
<td>168</td>
</tr>
<tr>
<td>LP$_{01}$ Dispersion (ps/nm/km)</td>
<td>21.0</td>
<td>21.2</td>
<td>20.9</td>
</tr>
<tr>
<td>LP$_{11}$ Cutoff ($\mu$m)</td>
<td>4.085</td>
<td>4.178</td>
<td>3.976</td>
</tr>
<tr>
<td>LP$_{11}$ Effective Area 1550 ($\mu$m$^2$)</td>
<td>238</td>
<td>242</td>
<td>234</td>
</tr>
<tr>
<td>LP$_{11}$ Dispersion (ps/nm/km)</td>
<td>21.1</td>
<td>21.4</td>
<td>20.8</td>
</tr>
<tr>
<td>DMGD at 1500 (ps/km)</td>
<td>-0.76</td>
<td>0.1012</td>
<td>-0.1243</td>
</tr>
<tr>
<td>DMGD at 1550 (ps/km)</td>
<td>0.39</td>
<td>0.1057</td>
<td>-0.1269</td>
</tr>
<tr>
<td>DMGD at 1600 (ps/km)</td>
<td>0.68</td>
<td>0.1094</td>
<td>-0.1304</td>
</tr>
<tr>
<td>DMGD slope at 1550 nm (ps/nm/km)</td>
<td>0.0191</td>
<td>0.06123</td>
<td>-0.04363</td>
</tr>
</tbody>
</table>

DMGD compensation has been demonstrated experimentally [68]. Fig. 15 shows the DMGD measured for four spools of fibers (A to D) with different refractive index designs. The lengths of the four fibers are 10, 18, 22 and 50 km, respectively. Fibers A and B have positive DMGD with negative DMGD slope. Fiber C has negative DMGD and positive DMGD slope. Fiber D was targeted to have near zero DMGD. The measured DMGD for this fiber was between about -0.20 to 0 ps/km, which are slight larger than the design target. To demonstrated DMGD compensation, we spliced the 18, 10 and 22-km spools together, and connected them to the 50-km spool with a connector to construct a 100-km link and measured the total DMGD. In Fig. 16, it is observed that average DMGD varies from $-6$ to $+5$ ps/km across the C-band from 1530 nm to 1565 nm. The measured attenuation for LP$_{01}$ and LP$_{11}$ in the link was approximately the same 0.25 dB/km.
Mode division multiplexing transmission over few mode fibers has been demonstrated in several system experiments. Table 3 summarizes a few most recent experiments that have been reported, which represent the state of the art in this area. The number of modes used in the transmission experiments is 3 or 6 that require 6x6 or 12x12 MIMO processing. A larger number of modes is possible but will increase significantly the complexity of MIMO and processing time. Few mode EDFAs using specially designed dopant profiles to equalize modal gain have demonstrated, but further optimization is required to improve further the FM EDFA performance and to extend to a larger number of modes. For the mode mux/demux devices, both devices using free space optics with phase plates and 3D-waveguides are demonstrated. Among them, the 3D-waveguide approach is more promising to extend to a large number of modes and to realize compact and integrated devices.

Table 3: Mode division multiplexing transmission experiments using few mode fibers

<table>
<thead>
<tr>
<th>Fiber</th>
<th>System</th>
<th>No of modes</th>
<th>DMGD (ps/km)</th>
<th>Span (km)</th>
<th>Mode Mux/Demux</th>
<th>Amplifier</th>
<th>Data rate (Gb/s)</th>
<th>No of channels</th>
<th>Channel spacing (GHz)</th>
<th>Reach length (km)</th>
<th>Total capacity (Tb/s)</th>
<th>Spectral efficiency (b/Hz)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>25</td>
<td>50</td>
<td>Phase pate</td>
<td>FM EDFA</td>
<td>76</td>
<td>146</td>
<td>25</td>
<td>500</td>
<td>66.57</td>
<td>18.2</td>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>183</td>
<td>59</td>
<td>3D-waveguide</td>
<td>SM EDFA</td>
<td>128</td>
<td>32</td>
<td>25</td>
<td>177</td>
<td>26.4</td>
<td>32.0</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5.4</td>
<td>84, 35</td>
<td>Phase pate</td>
<td>FM EDFA</td>
<td>128</td>
<td>96</td>
<td>50</td>
<td>119</td>
<td>57.6</td>
<td>12</td>
<td>76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>30</td>
<td>Phase pate</td>
<td>SM EDFA</td>
<td>80</td>
<td>1</td>
<td>1200</td>
<td>0.19</td>
<td>0.19</td>
<td>77</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IV-2 Multicore fibers

Multicore fiber is another potential fiber for space division multiplexing. Different multicore fiber structures have been proposed. Fig. 17 shows schematics of some MCF structure designs. Fig. 17(a) is hexagonal design. This design has the highest packing density. However, the crosstalk in the central core is the worst because it has 6 neighboring cores.
To avoid this problem, one can use one ring design as shown in Fig. 17(b). Fig. 17(c) is a linear array design. A linear array can have \( nxm \) cores, which can be designed to match semiconductor transceiver arrays. The designs of Fig. 17(a)-(c) have a round fiber cladding. One limitation of round fiber cladding is that the number of cores in a fiber is limited by the cladding diameter because if the cladding diameter is too large, the fiber loses its flexibility. To overcome this limit, we can use a ribbon MCF design as shown Fig. 17(d). A ribbon structure offers the advantage of scalability for number of cores in one dimension while keeping the other dimension small enough to maintain fiber flexibility in that dimension.

![Figure 17: Multicore fiber designs](a) (b) (c) (d)

One most important aspect for MCF designs is the crosstalk among the cores. The crosstalk depends on core refractive index profile designs and the distance between two neighboring cores. One way to model the crosstalk is to use the coupled mode theory [78]. Let’s consider two perfect identical cores separated by a distance \( D \). From the coupled mode theory, if we launch light into core 1, the powers \( P_1 \) and \( P_2 \) transmitted in two cores will change sinusoidally. The power crosstalk can be calculated using the following equation:

\[
X = 10 \log \left( \frac{P_2}{P_1} \right) = 10 \log \left( \frac{4\kappa^2}{4g^2\cot^2(gz) + (\Delta\beta)^2} \right)
\]

(9)

where \( z \) is the propagation distance, \( \kappa \) is the coupling coefficient, \( \Delta\beta \) is the mismatch in propagation constant between the modes in two cores when they are isolated, and \( g \) is a parameter depending on \( \kappa \) and \( \Delta\beta \),

\[
g^2 = \kappa^2 + \left( \frac{\Delta\beta}{2} \right)^2
\]

(10)

The crosstalk depends on the coupling coefficient \( \kappa \) that depends on the core design and distance between the two cores, and \( \Delta\beta \) that depends on the difference in refractive index profile between the two cores. This simple two-core model can provide good guidelines for designing MCFs although a more complicated model is needed to determine the crosstalk more accurately among all the cores in a MCF. According to Eq. (9), the most important factor to reduce the crosstalk is to reduce the coupling coefficient. The coupling coefficient depends on the overlap integral of electrical fields of the fundamental modes guided in two neighboring cores. Increasing the space between the two cores reduces the coupling coefficient but results in lower packing density. A low index trench around the core in the cladding is effective to confine the field closer to the core to suppress the crosstalk. Another factor is the mismatch in propagation constant between the two cores. A small mismatch reduces effectively the maximum power that can be transferred from one core to the other core. Therefore a heterogeneous core design can have lower crosstalk than homogeneous core design.

Eq. (9) shows that the power conversion efficiency oscillates sinusoidally with a coupling length of \( L = 2\pi/g \). If the fiber length is much less than the half of the coupling length, Eq. (9) can be used to calculate the crosstalk. However, for fiber length much longer than the coupling length, it was reported that the measured crosstalk of fabricated homogeneous MCFs did not oscillate as shown Eq. (9), but accumulated linearly along the fiber length [79]. In addition, the measured crosstalk of fabricated heterogeneous MCFs was reported to be \( \approx 40 \text{ dB} \) larger than the power conversion
Such discrepancies may be due to inhomogeneity of cores along the fiber and fiber bending effects. Taking into account fiber bending and statistical nature of crosstalk, a simple formula is derived for the average crosstalk:

\[
X = 2 \frac{\kappa^2}{\beta} \frac{R}{D} L
\]

where \( \kappa \) is the coupling coefficient, \( \beta \) is the propagation constant, \( R \) is bending radius, \( D \) is the distance between two cores, and \( L \) is the fiber length. Eq. (11) shows that the average crosstalk scales with fiber length, which explains the linear scaling of crosstalk observed in experiments.

To design a MCF with low crosstalk, it is important to reduce the overlap between the electrical fields of the two modes propagating in two neighboring cores. Step and trench assisted MFCs have been studied in detail in order to maximize the core density. Fig. 18 plots the crosstalk as a function of core spacing for step and trench assisted profiles designs. The crosstalk was calculated using Eq. (11) with coupling coefficients taken approximately from Ref. [82]. The bending radius used in the calculation was 50 cm, and the fiber length was 100 km. It can be seen that, for the effective area of 80 \( \mu \)m\(^2\) with a step profile design, the core spacing needs to be greater than 45 \( \mu \)m to ensure a crosstalk of less than -30 dB after 100 km propagation. With a trench profile design, the core spacing can be reduced to about 37 \( \mu \)m for the same effective area. Even for the effective area of 100 \( \mu \)m\(^2\), the core spacing is smaller than the step index with 80 \( \mu \)m\(^2\).

To accommodate more cores in a MCF, the cladding diameter can be increased. However, the fiber diameter is limited by the mechanical reliability requirements. It has been reported that the maximum fiber diameter should be smaller than 230 \( \mu \)m to ensure an acceptable failure rate under 50 mm bend radius. With this fiber diameter, the largest number of cores can be put into a multicore fiber is about 19 assuming the worst 100 km crosstalk.

![Fig. 18 Crosstalk as function of core spacing for step and trench assisted profiles designs.](image)

Low loss and low crosstalk MCFs have been demonstrated and used in transmission experiments using space division multiplexing. Table 4 summarizes most recent experiments on space division multiplexing transmission using MCFs, which represents the state of the art in MCF transmission. Total transmission capacity of over 1 Pb/s has been demonstrated with spectral efficiency around 100 b/Hz [84, 85]. Long distance transmission over 6000 km has been achieved using multicore EDFA [86]. Also, the number of core of 19 has been fabricated and used for a transmission experiment [87].

<table>
<thead>
<tr>
<th>Fiber diameter</th>
<th>Effective area</th>
<th>Span (km)</th>
<th>Data rate (Gb/s)</th>
<th>No of channels</th>
<th>Channel spacing</th>
<th>Reach length</th>
<th>Total capacity</th>
<th>Spectral efficiency</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of cores</td>
<td>Core spacing</td>
<td>Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Space division multiplexing transmission experiments using multicore fibers
MCFs are also attractive for high density short reach parallel optical data links. The use of VCSEL array and multicore fiber to realize multichannel transmission was proposed in Ref. [88], where a transmission over a 2x2 MCF using direct coupling with a linear VCSEL array at 1-Gb/s was demonstrated. Recently, a transmission over a hexagonal 7 core multimode MCF using tapered multicore connectors and 850-nm VCSELs was reported [89]. Also, MCFs with linear geometry arrangements have been proposed for used with Silicon Photonics linear array transceivers [90,91]. MCFs with 1x4 and a 2x4 linear array core arrangements have been made. It has been shown that a step index profile design with core separation of 47 μm resulted in crosstalk between two neighboring cores below -45 dB for fiber length of 200 m, which is suitable for short reach applications. In a recent report, a ribbon MCF with rectangular fiber cross-section has been demonstrated with low crosstalk [92].

IV-3 Challenges for practical space division multiplexing systems

Although significant progress has been made in both FMFs and MCFs and SDM transmission systems, there are still significant challenges for both the fibers and the components before they can be used in practical networks. From the fiber side, fiber manufacturing companies need to understand fiber design space and identify optimum fiber designs for both FMFs and MCFs in terms of crosstalk, mode coupling, multipath interference and attenuation. Most importantly, there is a need to develop practical low cost processes for large scale production FMFs and MCFs.

From the component side, component makers need to develop optical components for SDM systems including transceiver arrays, low cost multiplex and de-multiplex components, optical amplifiers for simultaneously amplifying multimodes or multicores, and precision coupling components and connectors. These components are more challenging to develop than FMFs and MCFs. In addition to developing SDM components, it is important to integrate these components together with transceivers and WDM components to form subsystems. Without subsystem integration, it will be hard to realize the cost benefits of SDM.

The current belief is that it will take many years to overcome the challenges mentioned above so there is still a long way to go before the SDM technologies can be used in real communications systems. However, multicore fibers may be used first in short reach applications because some of the components such as multicore amplifiers, mux/demux that are required for long haul transmissions are not needed for short reach links. In addition, MCFs can adapt transceiver linear arrays made with low cost silicon photonics, which has the potential to provide higher bandwidth-distance capability in meeting the power and density needs of data centers and high performance computer interconnects.

References:


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