New development in optical fibers for data center applications

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ABSTRACT

VCSEL-multimode optical fiber based links is the most successful optical technology in Data Centers. Laser-optimized multimode optical fibers, OM3 and OM4, have been the primary choice of physical media for 10 G serial, 4 x 10 G parallel, 10 x 10 G parallel, and 4 x 25 G parallel optical solutions in IEEE 802.3 standards. As the transition of high-end servers from 10 Gb/s to 40 Gb/s is driving the aggregation of speeds to 40 Gb/s now, and to 100 Gb/s and 400 Gb/s in near future, industry experts are coming together in IEEE 802.3bs 400 Gb/s study group and preliminary discussion of Terabit transmission for datacom applications has also been commenced. To meet the requirement of speed, capacity, density, power consumption and cost for next generation datacom applications, optical fiber design concepts beyond the standard OM3 and OM4 MMFs have a revived research and developmental interest, for example, wide band multimode optical fiber using multiple dopants for coarse wavelength division multiplexing; multicore multimode optical fiber using plural multimode cores in a single fiber strand to improve spatial density; and perhaps 50 Gb/s per lane and few mode fiber in spatial division multiplexing for ultimate capacity increase in far future. This talk reviews the multitude of fiber optic media being developed in the industry to address the upcoming challenges of datacom growth. We conclude that multimode transmission using low cost VCSEL technology will continue to be a viable solution for datacom applications.

Keywords: OM4, CWDM, data centers

1. INTRODUCTION

VCSEL-multimode optical fiber based links is the most successful optical technology in Data Centers. Parallel optical solutions based on 10 G serial line speed, using 12 F MPO and 2 x 12 F MPO interfaces, were standardized for 4 x 10 G (IEEE 802.3ba 40GBASE-SR4) and 10 x 10 G (IEEE 802.3ba 100GBASE-SR10) transmission in 2010, respectively. As the aggregation speeds in data centers take off at 40 Gb/s, and move to 100 Gb/s and 400 Gb/s in coming years, there are needs to reduce fiber counts in parallel cabling in order to decrease the spatial density and support future speeds to 400 Gb/s and Terabit transmission. Approaches such as increasing serial line speed at 25 Gb/s now and 50 Gb/s in the future and using wavelength division multiplexing (WDM) are implemented to reduce fiber counts and support higher speed. IEEE 802.3bm 100G-SR4 standard based on 25 G line speed is near completion and 400 G using 2 x 16 parallel fibers is proposed [1]. Using coarse WDM (CWDM), it would be possible to achieve 100 G on a single pair of MMF and 400 G on four pair of MMF, which allows to use the same 12 F cabling infrastructure of 40GBASE-SR4 and 100GBASE-SR4. The evolution of fiber cabling of laser optimized multimode fibers for high speed 40 G, 100 G and 400 G applications in Datacom industry is summarized in table 1.

Laser-optimized multimode optical fibers, OM3 and OM4, have been the primary choice of physical media for 10 G and 25 G line speeds in IEEE 802.3 standards. Recently, there is need to examine the capability of laser-optimized MMF to support 4 x 25 G CWDM application and estimate desired bandwidth across all four WDM windows. To meet the requirements of speed, capacity, density, power consumption and cost for next generation datacom applications, optical fiber design concepts beyond the standard OM3 and OM4 MMFs have a revived research and developmental interest, for example, wide band multimode optical fiber using multiple dopants for CWDM; multicore multimode optical fiber using plural multimode cores in a single fiber strand to improve spatial density; and perhaps 50 Gb/s per lane and few mode fiber in spatial division multiplexing for ultimate capacity increase in far future. This talk reviews the multitude of fiber optic media being developed in the industry to address the upcoming challenges of datacom growth.

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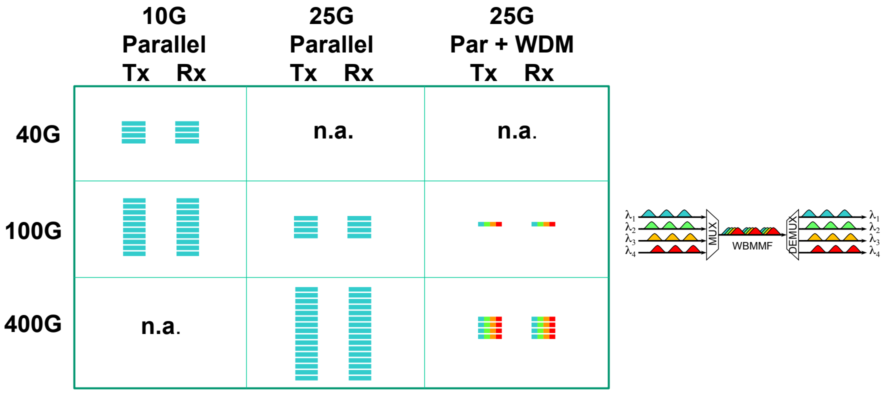
Table 1. The evolution map cabling of laser optimized multimode fibers in high speed datacom applications.



2. OM4 MMF AND APPLICATIONS TO HIGH SPEED TRANSMISSION IN DATACOM

2.1 Review of laser-optimized MMF

Laser-optimized MMF has a parabolic alpha core with 1% relative delta and a 50 µm core diameter. A modified version of the design profile with a trench in the profile was introduced to reduce bending loss and enable robust cabling installation. An illustration of the fiber index profile is shown in the inset of Fig. 1. The profile shape parameter alpha is optimized to maximize the modal bandwidth at 850 nm. The black line in Fig. 1 shows the modal bandwidth versus wavelength calculated using a simple equation in Refi's book [2]. Per TIA/EIA 492AAAD, OM4 MMF has an effective modal bandwidth larger than 4700 MHz*km at 850 nm. Note that EMB of OM4 is calculated using ten worst case weighting functions emulating statistical power distribution of VCSELs, which is different from the modal bandwidth in Fig. 1. The chromatic dispersion of the laser optimized MMF calculated using zero dispersion slope S_0 = 0.1028 ps/(nm^2*km) and zero dispersion wavelength λ_0 = 1316 nm per IEEE [3] is shown in red in Fig. 1. The absolute value of the chromatic dispersion decreases from ~ 103 ps/nm*km at 850 nm to ~ 65 ps/nm*km at 950 nm. This has important implications in considering CWDM applications discussed in the later section. It is worthy to note that the chromatic dispersion per IEEE parameters is more conservative than the chromatic dispersion of OM4 products by various vendors.

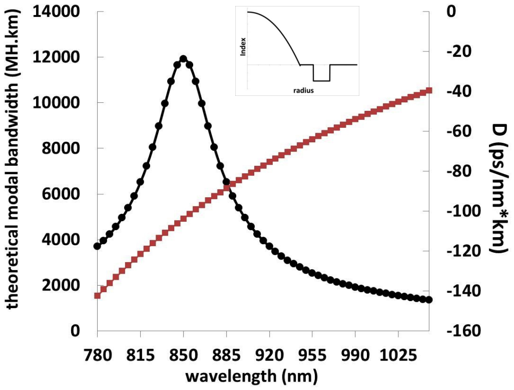


Figure 1. black: theoretical modal bandwidth of a 50/125 µm MMF optimized at 850 nm; red: chromatic dispersion versus wavelength per IEEE parameters; inset: refractive index profile.

2.2 OM4 in parallel optics transmission

10GBASE-SR link supports 300 m over OM3 MMF and 400 m over OM4 MMF. With tightened connector loss, error free transmission can be achieved over 550 m on OM4 MMF using 10GBASE-SR transceiver. Beyond 10 Gb/s, parallel optical transmission has been adopted in industry standards using multimode fiber as transmission medium. IEEE

P802.3ba 40GBASE-SR4 published in 2010 specifies 4 x 10 Gb/s using 12 F MPO interface. Among the 12 multimode fibers, 4 fibers transmit and 4 receive signals. IEEE P802.3ba 100GBASE-SR10 specifies 10 x 10 Gb/s using 2 x 12 F MPO interface. Middle 10 of the top 12 fibers transmit and the middle 10 of the bottom 12 fibers receive. 100GBASE-SR4 uses 12 F MPO interface, the same as 40GBASE-SR4, will be completed at the time this article is published. 128GFC will be similar to 100GBASE-SR4.

Migrating to 40 G using 40GBASE-SR4 transceiver, the supported link reach is reduced to 150 m on OM4 MMF, as a trade-off to relax transceiver specifications, e.g. the RMS spectral width of VCSEL is broadened to 0.65 nm. To overcome the reach limitation of 40GBASE-SR4 transceiver, the leading transceiver vendors including Avago, Finisar and Cisco developed premium 40 G transceivers with tightened specification including RMS spectral width to extend OM4 to the same coverage as at 10Gb/s. Fig. 2 shows an experimental demonstration of a 40GBASE-eSR4 transceiver on a 550 m OM4 MMF across a temperature range from 25 ^{o}C to 65 ^{o}C. The OM4 MMF under test has EMBc ~5171 MHz*km, close to OM4 specification limit. Error free transmission is achieved with maximum dispersion power penalty of 4.06 dB at 55^{o}C [4].

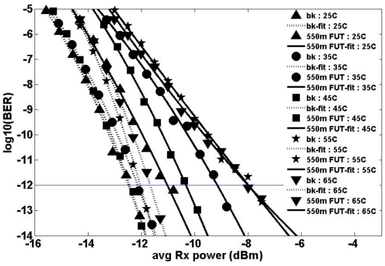


Figure 2. BER waterfall curves of a 550 m OM4 MMF from 25^{o}C to 65 ^{o}C using one channel of a 40GBASE-eSR4 transceiver.

Similarly, 100GBASE-SR4 standard specifies a reduced reach - 100 m on OM4 MMF, with a RMS spectral width of 0.6 nm. It is likely that the same business model, i.e. a premium transceiver specification, will be applied to the transceiver to extend the reach beyond 100 m.

Following the path of parallel optical solution, 400GBASE-SR16, using 2 x 16 fibers, is proposed. Transmission via parallel multimode fibers has pragmatic limits, e.g. 100GBASE-SR4 is more practical than 100GBASE-SR10. Above – SR16, the appeal of multimode optical fiber is diminished. A better solution than a simple parallel optical transmission is needed to keep MMF attractive in datacom applications.

2.3 OM4 in short wave WDM applications

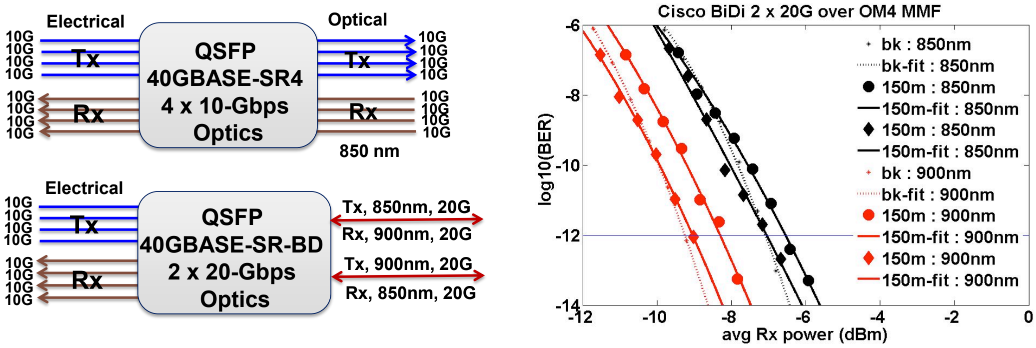


Figure 3. 40GBASE-SR-BD transmission. a) comparison between 40GBASE-SR4 and 40GBASE-SR-BD transceivers; b) BER waterfall curves of 2 x 20 G transmission over 150 m OM4 MMFs at 850 nm and 900 nm.

Concurrent with extending the reach of parallel fibers using premium transceivers, another trend is in reviving the value of using multiple wavelengths in MMF to maximize the utilization of fibers in existing fiber cable installations. Cisco's 40G-SR-BD uses two wavelengths centered around 850 nm and 900 nm in opposite directions per fiber at 20 Gb/s each. Same as IEEE P802.3ba 40GBASE-SR4 transceiver, 40G-SR-BD uses QSFP+ form factor. The electrical interfaces are four 10 Gb/s parallel lanes. What is different from 40GBASE-SR4 transceiver is that in 40G-SR-BD, the four 10 Gb/s electrical signals are multiplexed and converted into 2 by 20 Gb/s signal - one drives a VCSEL centered around 850 nm and the other centered around 900 nm. 40G-SR-BD transceiver enables 40 Gb/s transmission over a single pair of MMFs with LC interface. It is compatible with the fiber/cable infrastructure for existing 10 G or Gigabit applications. Figure 3a illustrates the similarity and difference between 40GBASE-SR4 transceiver and 40G-SR-BD transceiver. Figure 3b shows an example of system transmission over 150 m OM4 MMF using 40G-SR-BD transceivers. Bit error rate waterfall curves show that small dispersion power penalties are achieved at both 850 nm and 900 nm. It is estimated that EMB less than 3000 MHz*km at 900 nm is allowed to support 20 Gb/s over 150 m due to reduced chromatic dispersion and increased chromatic bandwidth at 900 nm.

3. WIDE BAND MULTIMODE FIBER FOR CWDM

3.1 Need for a wide band multimode fiber

As stated in the previous section, parallel optical cabling is a mature solution adopted in IEEE 40GBASE-SR4, 100GBASE-SR10 and 100GBASE-SR4 standards. However it has pragmatic limitation and loses its appeal with too many fiber counts. Data rate capacity improves significantly if cabling supports parallel connectivity and fiber supports multiple wavelengths. Back in 2005, Agilent's pioneering MAUI-CWDM parallel optics interconnect project demonstrated 250 Gb/s transmission over short reach standard 12F multimode ribbon at 990 nm, 1020 nm, 1050 nm and 1080 nm [5]. Wavelength division multiplexing over OM3 multimode optical fibers was explored using the same prototype CWDM transceiver. 4 x 10 Gb/s CWDM transmission over 300 m OM3 MMF was demonstrated at 990 nm, 1020 nm, 1050 nm and 1080 nm [6]. Electronic dispersion compensation was used after the receiver. VCSELs at longer wavelength favor adding Indium and Phosphide to GaAs to achieve faster speed. However it also benefits from fibers with bandwidth supporting longer wavelengths transmission. It can be achieved by shifting alpha of fibers doped with Germania only as shown in next section. Or, it can broaden the optimized alpha to a range of wavelengths via co-doping Germania with other materials [7,8,9,10,11]. An example of such fiber supporting wide band and high speed transmission at longer wavelength is shown in Fig. 4 below. The optical eyes showed some ISI at 1060 nm and completely closed at 1300 nm after 300 m standard OM3 MMF, however the optical eyes remained open after 300 m co-doped wide band MMF at those wavelengths with 10 Gb/s transmission (Fig. 4 left). Clean open eyes were obtained after 150 m of such a wide band MMF for all four channels of a prototype 4 x 25 Gb/s parallel transceiver centered at 1060 nm (Fig. 4 right). Though impressive results were demonstrated in the works referenced in this paragraph, none of them matured into commercial stage to gain industry consensus on a wide band MMF for CWDM applications.

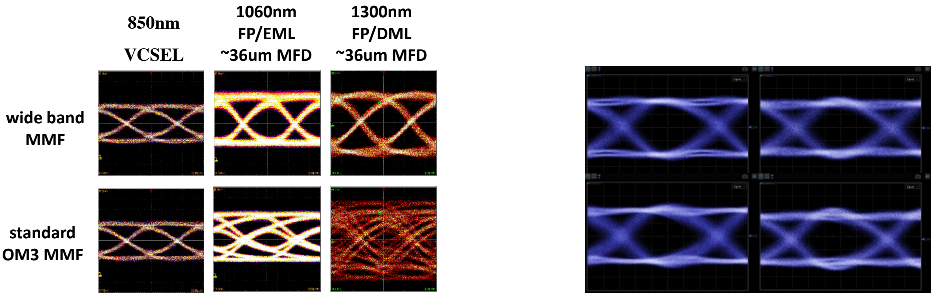


Figure 4. Left: 10 Gb/s optical eyes after 300 m wide band MMF (top) and standard OM3 MMF (bottom) at 850 nm, 1060 nm and 1300 nm. Right: Open eyes after 150 m wide band MMF using 4 x 25 Gbps transmitter and receiver at 1060 nm.

With the 2nd generation of 100 G standard approaching completion in IEEE, it is recognized that a fiber leveraging both the trend of parallel transmission and the trend of short-wave CWDM is favorable to meet the need of future speed of 400 G and 1.6 Tb in data centers. Such a fiber should meet following requirements: it must retain 850 nm application support, it must support 4 wavelengths with 30 nm spacing up to 950 nm for low-cost WDM. The implication of these requirements is that a new type of MMF is needed to have sufficient bandwidth not only around 850 nm, but across the four WDM windows from 850 nm to 950 nm.

3.2 Bandwidth requirement of a wide band MMF for CWDM

Per TIA/IEC 492AAAD, OM4 MMF is specified to have EMB > 4700 MHz*km at 850 nm. Theoretically the fiber is designed to have alpha optimized for modal bandwidth peaking at 850 nm. However alpha is a sensitivity parameter, which in manufacturing practice results in a natural statistical distribution of values either larger or smaller than the optimized one and BW still meets the EMB > 4700 MHz*km requirement at 850 nm. As illustrated in Fig. 5, the largest wavelength for peak modal bandwidth is at 905 nm to maintain a 4700 MHz*km BW at 850 nm. The fiber with the same BW at 850 nm but smaller alpha has higher BW at wavelength > 850 nm and thus benefits longer wavelength transmission as shown in Fig. 5. Note that the modal bandwidth in Fig. 5 is calculated with a simple equation in Ref [2]. It is different from the definition of EMB for laser-optimized MMF but convenient to illustrate the variation of the peak modal bandwidth in manufacturing. The chromatic bandwidth increases from 3000 MHz*km at 850 nm to 4760 MHz*km at 950 nm for a source with RMS spectral width of 0.6 nm. The overall bandwidth of the fiber link is a combination of the modal bandwidth and chromatic bandwidth. Since the chromatic bandwidth is larger at longer wavelength, modal bandwidth is allowed to be smaller at longer wavelength to maintain the same system performance at 850 nm.

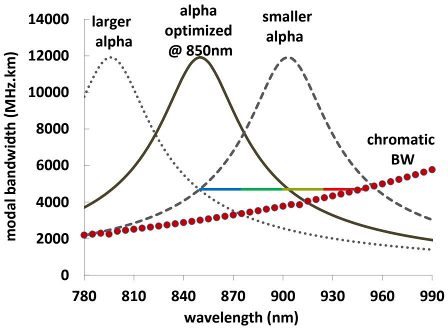


Figure 5. Modal bandwidth versus wavelengths for alpha variation and chromatic bandwidth versus wavelength.

System performance of a VCSEL-fiber link has multiple sources of penalties including attenuation, inter-symbol-interference (ISI), jitter, relative intensity noise (RIN) and modal partition noise (MPN). It is convenient to use the IEEE excel spreadsheet modeling for 100GBASE-SR4 [3] to evaluate the system performance of CWDM and estimate the effective modal bandwidth required at longer wavelengths to maintain the same performance of 25 Gb/s at 850 nm. The RMS spectral width is taken as 0.6 nm for all wavelengths evaluated. The total power budget is 8.2 dB and 1.5 dB is assigned to connector loss. All parameters remain the same except that the effective modal bandwidth is adjusted to achieve zero margin for 100 m reach when wavelength is changed. Fig. 6 shows that penalties due to ISI, jitter, and RIN are dominant penalties at 100 m reach and don't change much versus wavelength. Penalties due to modal partition noise and attenuation decrease as wavelength increases with a value of 0.09 dB and 0.35 dB at 850 nm, respectively. The effective modal bandwidths required to obtain the zero link margin are : > 4700 MHz*km at 850 nm, > 3300 MHz*km at 875 nm, > 2900 MHz*km at 900 nm, > 2700 MHz*km at 925 nm, > 2550 MHz*km at 950 nm. The bandwidths versus wavelengths of an example wide-band compliant MMF are shown in Fig. 7. The estimated effective modal bandwidth value per IEEE spreadsheet is shown as the benchmark.

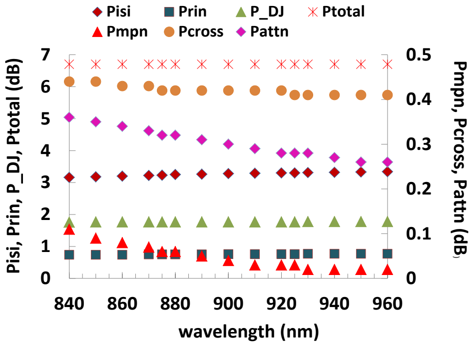


Figure 6. System penalties at 100 m reach versus wavelength per IEEE excel spreadsheet modeling for 100GBASE-SR4 [3].

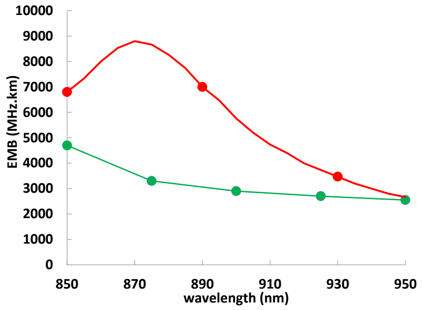


Figure 7. EMB of a wide-band compliant MMF versus wavelength (red) and minimum EMB estimated per IEEE spreadsheet (green).

4. FURTHER IMPROVEMENTS FOR CAPACITY-DISTANCE

Beyond premium transceiver to extend the reach of laser-optimized MMF and wide band MMF to increase the capacity of parallel optical links, other approaches to meet the density, capacity, reach and cost of future data centers include multicore MMF with integrated VCSEL array based transceivers, multicore single mode fiber with silicon-photonics transceiver, and perhaps MMFs for spatial division multiplexing.

Multicore MMF reduces the core-core connector spacing from 250 µm in a ribbon of parallel fibers to tens of microns in a single strand of fiber. A low cross talk MC-MMF embodying seven cores of 26 µm diameter was fabricated. Fig. 8 depicts the system performance of 100 m and 550 m MC-MMF at 10 Gb/s each core. The dispersion power penalties at BER = 10^{-12} is negligible at 100 m reach and less than 2.5 dB at 550 m reach, indicating good margin at an aggregate of 70 Gb/s over the same link coverage of 10GBASE-SR on standard OM4 MMF [12].

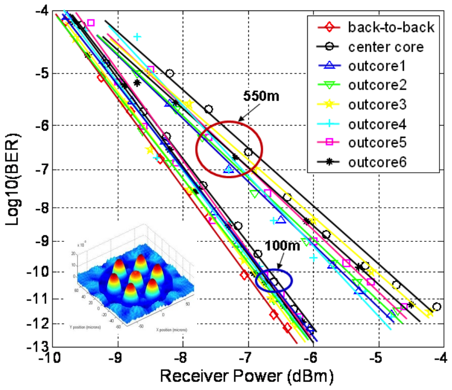


Figure 8. BER results for 100 m and 550 m links at 10 Gb/s in each core for an aggregate of 70 Gb/s through a MC-MMF [12].

Silicon photonics (SiPh) technology is a potentially disruptive technology that may reduce cost of single-mode fiber transceivers for many applications including datacenters. Due to its much smaller waveguide (0.2 µm to 3 µm) and high numerical aperture, the coupling loss to optical fiber is high. Coupling MMF to SiPh receiver is challenging. A single mode multicore fiber with a 2 x 4 rectangular core configuration is suitable for SiPh applications. The cost of SiPh is not likely to be competitive to VCSEL-MMF links in short reach space (< 500 m). Fundamentally, VCSELs have lower power consumption (pJ/bit) for short reach MM interconnects allowing higher density; VCSELs are smaller in size allowing higher bandwidth density [13]. VCSELs operating at speeds of up to 60 Gb/s have been reported [14, 15]. For short-reach links VCSEL/MMF solution may offer cost benefits over SiPh for line speeds of up to ~50-60 G, possibly higher.

Mode division multiplexing (MDM) exploits spatial modes of the optical fiber as a way to expand optical transmission link capacity in addition to wavelength multiplexing and serial line speed improvement. MMF naturally has many spatial modes. Laser optimized MMF has over 100 LP modes at 850 nm and 30 LP modes at 1550 nm (Fig. 9). Recently, 23 Tbit/s transmission was demonstrated using 17 km conventional 50/125 µm MMF [16]. In the far future, the ultimate capacity demand of datacom may resolve to use MDM on few-mode fiber or MMF.

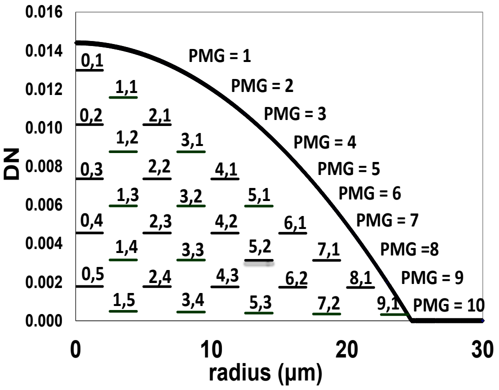


Figure 9. LP modes of 50/125 um MMF at 1550 nm.

5. CONCLUSIONS

In summary, premium transceivers with tightened specification preserve the reach of OM4 MMF at 40 Gb/s and 100 Gb/s. Wide band MMF supporting 25 Gb/s from 850 nm to 950 nm for CWDM is investigated for 400 Gb/s transmission. The results indicate that low cost VCSEL-based solutions over multimode fibers will continue to provide viable solutions to meet the challenges of future datacom applications.

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