

# Next Generation Wideband Multimode Fiber for Shortwave Wavelength Division Multiplexing in Datacom Links

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**ABSTRACT** In this paper, we report on the design, fabrication and bit error ratio (BER) testing of next generation wideband multimode fiber (NG WBMMF). The fiber is designed to support at least 4 communication channels at wavelengths between 850 and 950 nm at speeds of up to 28 Gb/s while guaranteeing the same performance as a standard OM4 MMF at 850 nm. Initial systems testing results indicate that the fiber can potentially extend MMF link lengths up to 300 m at a pre-Forward Error Corrected (pre-FEC) BER while delivering a combined 100 Gb/s transmission speed in a duplex link.

## 1. INTRODUCTION

Rapidly increasing internet data traffic as well as growth in cloud based services and storage has led to an exponential growth in datacenter traffic. Three quarters of this traffic are confined inside datacenters and require matching increases in the data carrying capacity of links within datacenters<sup>1</sup>. Reliable, energy efficient and cost effective short reach optical interconnects based on 850 nm VCSELs and laser optimized OM4 and OM3 multimode fibers currently carry bulk of the traffic inside datacenters and provide solutions at speeds of up to 100 Gb/s. For the future, the IEEE P802.3 bs Task Force is working towards adoption of 400 Gb/s standard by 2017<sup>2</sup>) and the T11 Technical Committee is commencing its work on the next Fibre Channel 64/256GFC standard for SAN with the target completion date in the middle of 2017<sup>3</sup>).

Short reach multimode links operating faster than 28 Gb/s use multiple parallel fibers to provide the required bandwidth. In order to go beyond the Space Division Multiplexing (SDM) approach and increase wavelength density of links, Shortwave Wavelength Division Multiplexing (SWDM) around 850 nm offers a viable alternative, particularly due to its backward compatibility with the existing installed infrastructure<sup>4,5</sup>). It is important, however, to improve performance of multimode fibers at longer wavelengths, which can be done by both stan-

standardizing fiber performance at longer wavelengths<sup>6</sup>) and by developing a next generation of MMFs that improve fiber bandwidth beyond 850 nm.

In this paper, we will demonstrate a new wideband multimode fiber with a wider bandwidth window in respect to the wavelength as compared to a standard OM4 fiber. An operational window supporting 4 wavelengths between 850 to 950 nm is targeted, assuming approximately 30 nm wavelength separation between VCSELs. Such a wide separation is important from the total link cost point of view. This separation accounts for both the pass-band and the guard-band and voids the need for the VCSEL temperature control and wavelength stabilization, relaxing requirements for multiplexer-demultiplexer. A wider bandwidth window will allow longer reaches at longer wavelengths when compared with a standard OM4 fiber and will support both duplex 100 Gb/s links and second generation 400 Gb/s links by using 4 wavelengths at 25 Gb/s over 4 fibers.

## 2. REQUIREMENTS FOR THE WBMMF

High chromatic dispersion around 100 ps/nm/km in MMF at 850 nm is the dominant fiber parameter that limits the link reach in modern high bandwidth fibers. Dispersion is lower at longer wavelengths, e.g. around 65 ps/nm/km at 950 nm, and this, together with the lower fiber attenuation, presents an opportunity to decrease fiber modal bandwidth requirements at longer wavelength channels.

Current spreadsheets for both 100 Gb/s Ethernet<sup>7</sup>) and 32GFC Fibre Channel<sup>8</sup>) take these changes in fiber properties with wavelength into account. A TIA T42.11/12 Joint Task Group is currently working on standardization of the wideband MMF and has adopted both spreadsheets for setting the wideband fiber bandwidth require-

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ments. The JTG is developing a full set of fiber specifications with the goal of issuing the WBMMF standard in 2016. So far, preliminary agreements have been reached to define the wavelength range from 846 nm to 953 nm and to tighten fiber chromatic dispersion specifications in this range. One of the explicit and important goals of the JTG is to make sure that the new WB fiber is fully backward compatible with existing OM4 MMF.

Both spreadsheets converge to similar fiber effective modal bandwidth (EMB) values when used to obtain zero margins for a 100 meter reach link power budget between 846 and 953 nm. Slightly more conservative Fibre Channel spreadsheet values are shown in Table 1 at arbitrary wavelength spacing.

**Table 1** Minimum EMB required to obtain a zero margin in a 100 m link power budget per 32GFC spreadsheet.

Wavelength, nm	EMB, MHz.km
846	4270
850	4700*
875	3300
900	2900
925	2700
950	2550
953	2535

\* Required for backward compatibility with a standard OM4 MMF and to ensure the worst case bandwidth at 840 nm.

The worst case VCSEL RMS spectral width is assumed to be 0.60 nm for Ethernet and 0.57 nm for FC. All other transceiver parameters such as rise-fall times, RIN, receiver bandwidth and sensitivity are assumed to be the same for the wavelength range. Link penalties improve or show little change with increasing wavelength with an ISI penalty remaining under 3.5 dB.

### 3. NEXT GENERATION WBMMF DESIGN

A high speed communication link using MMF requires that the shape of the refractive index profile of the core is optimized to minimize propagation delays of principal mode groups and to obtain the highest bandwidth at the operational wavelength.

$$\alpha_{opt} = 2 + y - \Delta \frac{(4+y)(3+y)}{(5+2y)} \quad (1)$$

where

$$y = - \left( \frac{2n_1 \lambda}{N_1} \frac{d\Delta}{d\lambda} \right) \quad (2)$$

and  $n_1$  is the maximum value of the core refractive index,  $n_2$  is the refractive index of the cladding,  $\Delta = (n_1^2 - n_2^2) / (2n_1^2)$ , and  $N_1$  is a material group index of the core:

$$N_1 = n_1 - \lambda \frac{dn_1}{d\lambda} \quad (3)$$

As can be seen from equations 1 to 3, the optimum profile shape depends on core and cladding material composition. Refractive index profile dispersion is significant in standard MMFs<sup>9)</sup> as these fibers are designed to have the highest EMB at 850 nm and EMB decreases for wavelengths away from the peak.

While it is possible to fabricate a standard MMF that complies with minimum EMB requirements for a wideband fiber as described in the previous section, it is desirable to make a wider bandwidth fiber to create a more robust product from the point of view of improved systems performance.

For an SWDM-based transmission system, this translates to decreasing dependence of the optimum profile shape on the wavelength and increasing the EMB spectral width. We designed such a NG WBMMF. The design optimization algorithm took into account desirable fiber EMB performance and other properties as well as practical considerations of an optical fiber fabrication process.

### 4. FIBER FABRICATION

Bend-optimized NG WBMMF samples were fabricated using the same process that is used for standard OM4 Bend-Optimized MMF (BOMMF). Full characterization of optical and geometrical parameters was performed on these samples and indicated no deviation from target baseline specifications that were also in accord with the standard BOMMF, see Table 2.

**Table 2** Geometry and optical data on NG WBMMF samples (\*).

Core / Cladding diameter, $\mu\text{m}$	49.6 / 125.0	$\pm 2.0 / \pm 0.5$
Core Non-circularity, %	$\leq 1.0$	—
NA	0.2	$\pm 0.010$
Attenuation (850 / 950 nm), dB/km	$\leq 2.1 / 1.4$	—
Chromatic dispersion (850 / 950 nm), ps/nm/km	94 / 59 <sup>(§)</sup>	—

\* At 850 nm unless indicated otherwise; § calculated from a dual window fit.

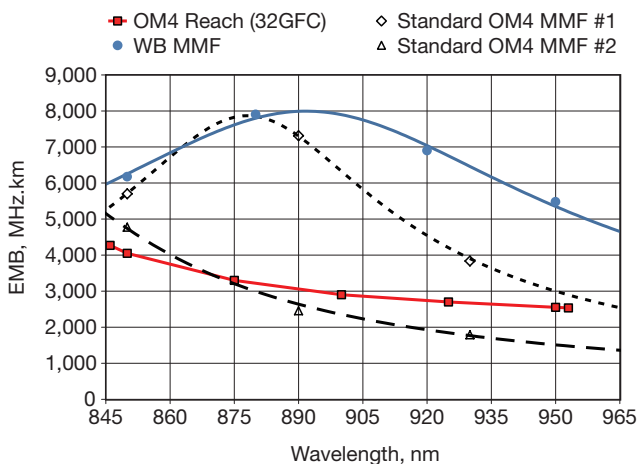
FOTP-220 compliant high resolution DMD tests were performed on WBMMF samples using a tunable picosecond Ti-Al<sub>2</sub>O<sub>3</sub> laser as a source at wavelengths between 850 and 950 nm. EMB values were calculated using 10 standard VCSEL weighting functions originally developed for 850 nm sources. The fiber refractive index profile was tuned to a peak EMB at around 880 nm in order to enhance fiber performance at 950 nm end of the range. EMB and the calculated overfill modal bandwidth (OMBc) data on one of the samples is shown in Table 3 as an illustration of the NG WBMMF performance.

**Table 3 HR DMD Data on a NG WBMMF Sample.**

EMB at 850 nm, MHz.km	6174
EMB at 880 nm, MHz.km	7902
EMB at 920 nm, MHz.km	6900
EMB at 950 nm, MHz.km	5478
OMBc at 850 nm, MHz.km	6963
OMBc at 880 nm, MHz.km	7753
OMBc at 920 nm, MHz.km	6350
OMBc at 950 nm, MHz.km	4114

EMB versus wavelength data from Table 3 is plotted in Figure 1.

Data for two standard OM4 MMFs is also shown for comparison with the #1 fiber passing the minimum OM4 reach requirements and the #2 fiber failing the 950 nm EMB due to a profile shape causing EMB to peak at shorter wavelengths. Both standard OM4 #1 and NG WBMMF have comparable peak EMBs and EMBs at 850 nm, however NG WBMMF significantly outperforms at longer wavelengths with almost double the bandwidth of the OM4 at 950 nm.



**Figure 1 EMB vs wavelength data for both standard OM4 and NG WBMMF; OM4 reach BW requirements per 32GFC spreadsheet are shown in red (squares).**

## 5. 100 Gb/s SWDM TRANSMISSION OVER NG WBMMF

BER tests on the NG WBMMF were performed in order to demonstrate fiber's ability to support 4 transmission channels between 850 and 950 nm and showcase its potential for longer than 100 m reach.

Four prototype SWDM TOSAs and one wideband ROSA provided by Finisar are used in the 100 G SWDM transmission experiment. Table 4 shows the characterization of the TOSAs and the ROSA at the driven condition for the transmission test. All TOSAs are driven at  $I = 11$  mA and differential RF amplitude  $\sim 1$  Vpp. The VCSELs were driven at 11 mA bias current to push the spectral widths as high as possible, towards the worst-case 0.60 nm value, to challenge performance. The center wavelength and RMS spectral width are 854.39 nm and 0.47 nm for TOSA 1, 881.83 nm and 0.53 nm for TOSA 2, 912.54 nm and 0.52 nm for TOSA 3, 944.68 nm and 0.60 nm for TOSA 4, respectively.

Encircled flux of all four TOSAs is compliant to the 100 G BASE-SR4 specification. Extinction ratio (ER) is around 4 dB for all TOSAs. Wide band ROSA has good responsivity at four wavelengths span of  $\sim 100$  nm window.

A schematic of the 100 G SWDM transmission test bed is shown in Figure 2. One channel of a four channel 28 G BERT from Multilane is used to drive the TOSA and detect the signal from ROSA. The BERT has slightly higher intrinsic jitter since it is a model designed for jitter compliance testing. The bit rate was 25.78215 Gb/s and signal pattern was PRBS31 NRZ. The differential RF signals from pattern generator are coupled to the TOSA by two identical high bandwidth bias tees. DC current from the laser driver (LDX-3412) is coupled to the TOSA through the DC port of the two bias tees.

The optical signal from the TOSA is launched into a 50/125  $\mu\text{m}$  jumper with LC interface, then to the NG WBMMF under test at various cut lengths (100 m, 200 m, 250 m, and 300 m). The optical eyes are recorded using the Keysight Infiniium DCA-X 86100D scope and the 86105D 30 G optical head. The eyes remain open after 300 m of NG WBMMFs, as shown in Figure 3.

**Table 4 SWDM TOSA/ROSA characterization.**

SWDM TOSA ID	Driven current (mA)	Center wavelength (nm)	RMS Spectral width (nm)	ER (dB)	Flux @ $r = 4.5 \mu\text{m}$ (%)	Flux @ $r = 19 \mu\text{m}$ (%)	Rx CTLE Setting (dB)	ROSA Responsivity (A/W)
850 nm	11	854.39	0.47	3.87	13.78	95.21	6.7	0.45
880 nm	11	881.83	0.53	4.08	14.07	95.84	6.7	0.42
910 nm	11	912.54	0.52	4.32	13.24	96.17	6.7	0.41
940 nm	11	944.68	0.6	4.09	11.56	96.09	6.7	0.52

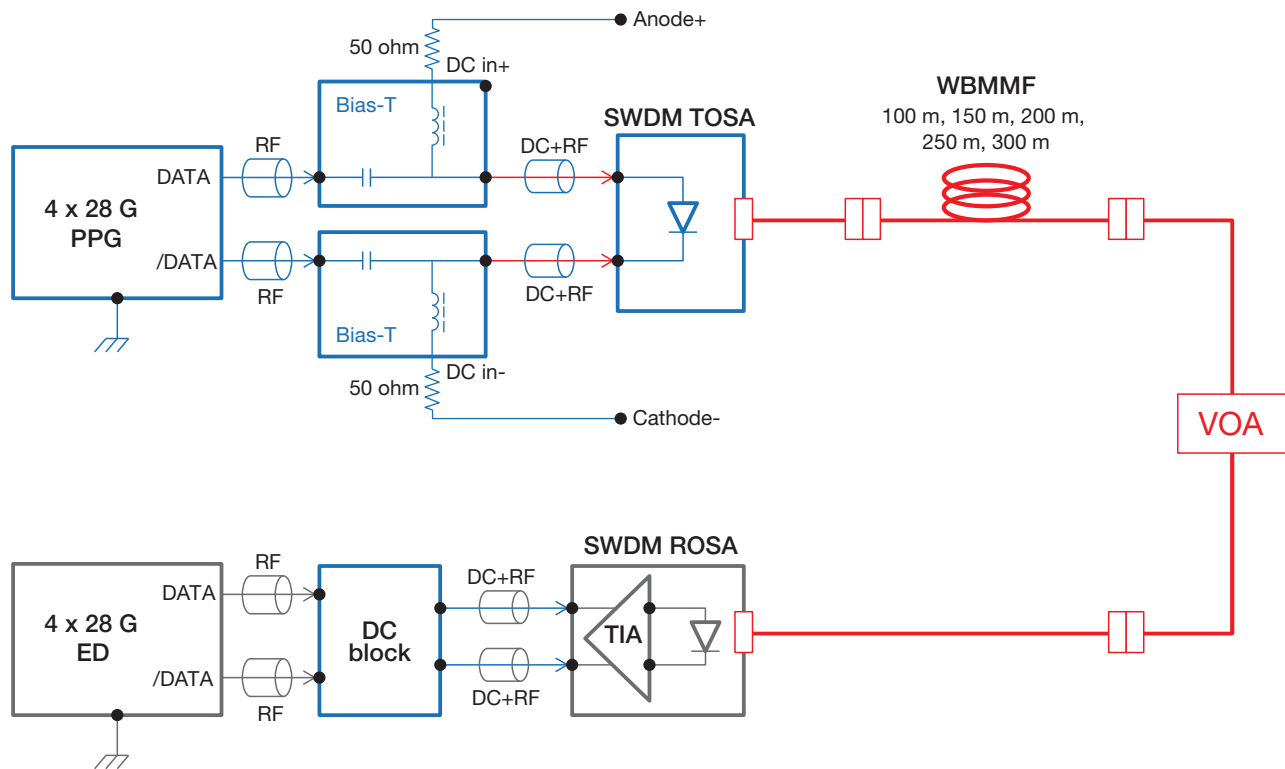


Figure 2 Schematic of the 100 Gb/s SWDM transmission over NG WBMMFs.

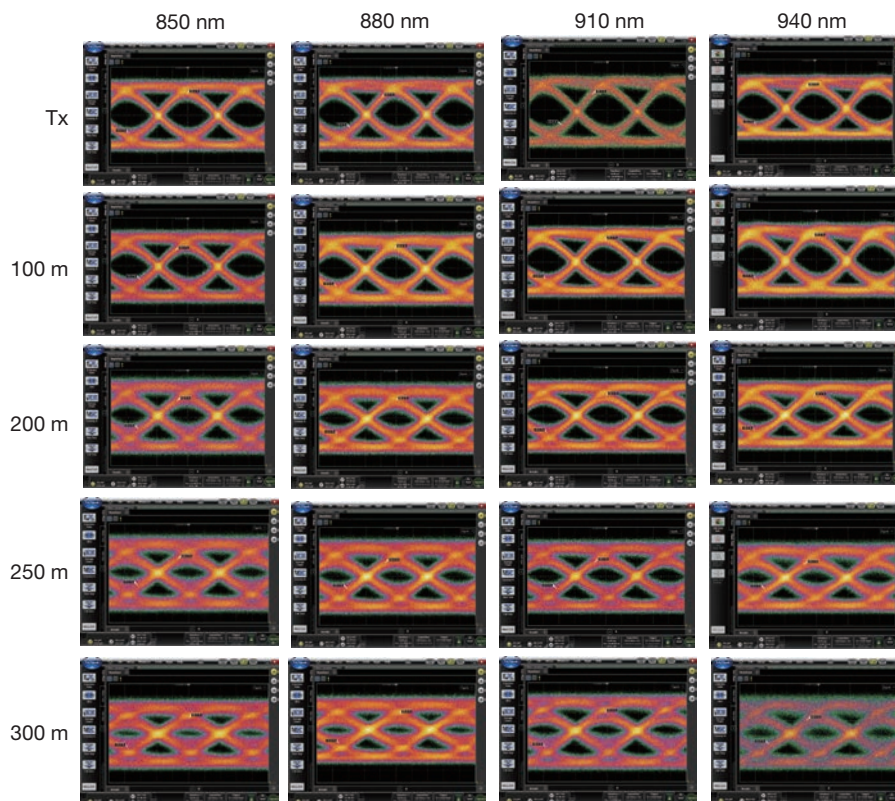


Figure 3 Optical eyes of the 100 G SWDM transmission over NG WBMMFs at various lengths (100 m, 200 m, 250 m, and 300 m).

For the bit error ratio waterfall curve testing, a variable optical attenuator (VOA) is placed after the NG WBMMF. The optical signal is received by the wide band ROSA through another 50/125  $\mu\text{m}$  jumper with LC interface. Differential signals after the transimpedance amplifiers (TIA) of the ROSA are coupled to the error detector through a 40 G DC block. Continuous time linear equalization (CTLE) is available in the error detector. CTLE = 6.7 dB is used to improve BER. Bit error ratio waterfall curves of the back to back link and on NG WBMMF at various lengths are shown in Figure 4. With sufficient received power, the pre-FEC bit error ratio is below FEC threshold ( $5 \times 10^{-5}$ ) up to 300 m for all four wavelengths. The dispersion penalties at  $5 \times 10^{-5}$  are less than 5 dB across the SWDM window on 300 m NG WBMMF. The penalties for 250 m transmission are less  $\leq 3$  dB at a stable operating point of  $5 \times 10^{-7}$  BER.

## 6. DISCUSSION

The pre-FEC reach of 300 m at 25 Gb/s clearly demonstrates that the new NG WBMMF is capable of exceeding the standard OM4 100 m reach on all 4 SDWM wavelengths when used with an equalizer. The reach will cover most datacenter connectivity needs with various link length distributions within datacenters showing that close

to 90% of multimode links are less than 100 m with the average link length of 54 m and 95% of switch-to-switch links shorter than 150 m<sup>10,11</sup>). The SWDM approach preserves backward compatibility with existing 850 nm transceivers making NG WBMMF a drop-in replacement for standard OM4 MMF, while also demonstrating a path towards 50 Gb/s lanes at longer wavelengths. Bend-optimized wideband OM4 MMF has recently become commercially available from OFS Fitel. The fiber supports 100 m reach in the 846-953 nm window as defined in 100 GBASE-SR4 and 32GFC link models<sup>12</sup>).

## 7. CONCLUSIONS

Short wave WDM over MMF is a promising new approach to meet ever increasing bandwidth demands in datacom and HPC arena. The NG WBMMF demonstrated here will facilitate implementation and transition to this new technology by allowing full backward compatibility with existing transceivers and by future-proofing new cable installations. BER tests at all four wavelengths within the 850 to 950 nm range demonstrate the fiber's potential to significantly extend the 100 m reach targeted on standard OM4 fibers and to provide a viable path to extended reaches for both 100 Gb/s duplex fiber links and for the next generation of 8 fiber 400 Gb/s and 800 Gb/s links.

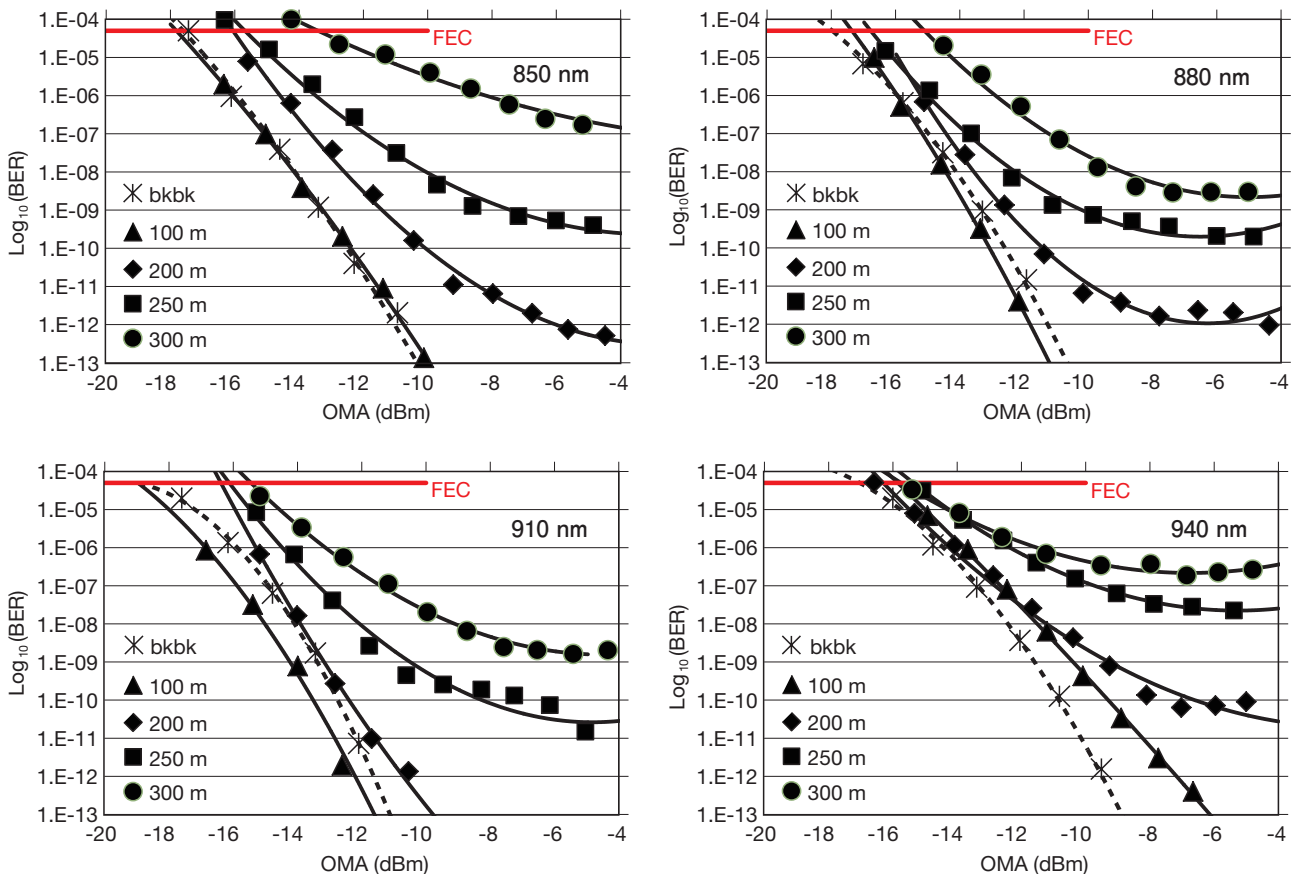


Figure 4 Bit error ratio of the 100 G SWDM transmission over NG WBMMFs at various length (100 m, 200 m, 250 m, and 300 m).

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### REFERENCES

- 1) "Cisco Global Cloud Index: Forecast and Methodology, 2013–2018," Cisco, 2014.
- 2) "IEEE P802.3bs 400 Gb/s Ethernet Task Force." [http://www.ieee802.org/3/bs/timeline\\_3bs\\_0514.pdf](http://www.ieee802.org/3/bs/timeline_3bs_0514.pdf)
- 3) "Proposal for a New INCITS Standard Fibre Channel-Physical Interfaces -7 (FC-PI-7) T11/14-302v1." [http://www.t11.org/ftp/t11/admin/project\\_proposals/14-302v1.pdf](http://www.t11.org/ftp/t11/admin/project_proposals/14-302v1.pdf)
- 4) R. Shubochkin, K. Balemarthy, Y. Sun, J. Kim, R. Lingle Jr, D.S. Vaidya, and J. Kamino, "Trends in datacom optical links," in *Proceedings of the 62nd IWCS*, Charlotte, NC, USA, 2013, pp. 633–642.
- 5) J.A. Tatum, D. Gazula, L.A. Graham, J.K. Guenter, R.H. Johnson, J. King, C. Kocot, G.D. Landry, I. Lyubomirsky, A.N. MacInnes, E.M. Shaw, K. Balemarthy, R. Shubochkin, D. Vaidya, M. Yan, and F. Tang, "VCSEL-Based Interconnects for Current and Future Data Centers," *J. Light. Technol.*, vol. 33, no. 4, pp. 727–732, Feb. 2015.
- 6) P. Kolesar, "TIA TR42.12: Project Initiation and Authorization for WBMMF detailed specification." 2014.
- 7) "100GbE ExampleMMF LinkModel 130503," Jun. 2012.. [www.ieee802.org/3/bm/public/may13/examplemmf%20linkmodel%20%20130503.xlsx](http://www.ieee802.org/3/bm/public/may13/examplemmf%20linkmodel%20%20130503.xlsx)
- 8) "MMF Link Model Spreadsheet for 32GFC," Sep. 2012.. <http://www.t11.org/t11/docreg.nsf/udocs/201237600>
- 9) J.W. Fleming, "Dispersion in GeO<sub>2</sub>-SiO<sub>2</sub> glasses," *Appl. Opt.*, vol. 23, no. 24, pp. 4486–4493, Dec. 1984.
- 10) A. Flatman, "Data centre link lengths," Nov. 2012.. [http://www.ieee802.org/3/ngbaset/public/nov12/flatman\\_01a\\_1112\\_ngbt.pdf](http://www.ieee802.org/3/ngbaset/public/nov12/flatman_01a_1112_ngbt.pdf)
- 11) A. Flatman, "Data centre link lengths & deployment of optical fibre," Sep. 2011.. [http://www.ieee802.org/3/100ngoptx/public/sept11/flatman\\_01\\_0911\\_ng100optx.pdf](http://www.ieee802.org/3/100ngoptx/public/sept11/flatman_01_0911_ng100optx.pdf)
- 12) "LaserWave® FLEX WideBand Fibers." <http://fiber-optic-catalog.ofsoptics.com/item/multimode-optical-fibers/high-performance-multimode-optical-fibers/laserwave-i-flex-i-wideband-fibers>