The Impact of Effective Modal Bandwidth on 100G SWDM Transmission over 250 m OM5 and Left-Tilt OM4 Multimode Fibers

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Abstract—We demonstrate 100G SWDM4 transmission over 250 m OM5 and left-tilt OM4 multimode fibers. The OM5 fibers are compliant to TIA-492AAAE and the left-tilt OM4 fibers are compliant only to TIA-492AADD and have a bandwidth peak at a wavelength longer than 850 nm. The “left-tilt” descriptor refers to the leftward leaning slope of the differential mode delay peaks. This is an indication that the peak bandwidth is at a wavelength longer than the measurement wavelength. To measure the margin to the FEC limit, 24 250 m channels were constructed from two links of 100 m and 150 m using either left-tilt OM4 or OM5 fiber. Error-free performance was achieved with each of the 24 OM5 channels. None of the 24 left-tilt OM4 channels achieved error-free performance. To further characterize performance, the effective modal bandwidth (EMB) was measured for 6 left-tilt OM4 fibers and 12 OM5 fibers from the same spools as the fibers used in the margin measurements. The OM4 fibers all have a left tilt at 850 nm and the OM5 fibers have either a left or right tilt. BER vs. received power was then measured over 250 m of these fibers. With the OM4 fibers, the long wavelength channels limited the system performance due to low modal bandwidth at longer wavelengths despite the left tilt at 850 nm. We demonstrate the relationship between effective modal bandwidth at 953 nm and BER performance at 910 and 940 nm.

Index Terms—Optical fibers, Optical fiber testing, Optical fiber dispersion, Multimode fiber

I. INTRODUCTION

The wideband multimode fiber cabling known as OM5 is the first and only multimode cable specified for wavelength division multiplexing (WDM). The fiber used in OM5 cabling was recently standardized in TIA-492AAAE [1] and IEC 60793-2-10 Ed.6 [2]. The nominal operating wavelengths for 4-wavelength short wave division multiplexing (SWDM4) are 850, 880, 910, and 940 nm. At these wavelengths systems operating at 100 Gbit/s [3-5], and 200 Gbit/s [6] have been demonstrated. The SWDM Alliance has published an MSA [7] for transceivers operating at 100 Gbit/s with 25 Gbit/s wavelength channels at these wavelengths.

TIA-492AAAE specifies the minimum effective modal bandwidth (EMB) of OM5 fiber at two wavelengths spanning this range to ensure sufficient performance for each wavelength channel. OM3 and OM4 fibers only specify EMB at 850 nm with values of ≥2000 MHz*km for OM3 fiber and ≥4700 MHz*km for OM4 fiber. With OM5 fibers, EMB values of ≥4700 MHz*km at 850 nm and ≥2470 MHz*km at 953 nm are required.

The EMB of a fiber is measured using the differential mode delay (DMD) technique as outlined in FOTP-220 [8] and IEC 60793-1-49 Ed. 2.0 [9]. DMD measurements result in plots like the ones in Fig. 1 which show the output pulse of a multimode fiber under test where the input pulse from a single-mode probe fiber is scanned across the core of the fiber under test. It has been proposed [10-12] that “left-tilt” OM4 fibers where the DMD traces tilt up and to the left at 850 nm (like Fig. 1) over a range of radial offsets may be suitable for WDM transmission because these fibers have a bandwidth peak at wavelengths longer than 850 nm and potentially higher values of EMB at longer wavelengths. These select OM4 fibers may offset chromatic dispersion and modal dispersion under certain launch conditions [13-18]. However, these launch conditions have not been standardized and cannot be guaranteed when using standards compliant transceivers.

In this paper, we investigate channel performance of 100G SWDM4 transceivers over 250 m reaches using fibers that are OM5 compliant and over OM4 fibers that have a bandwidth peak shifted to longer wavelengths and a DMD plot with left tilt. Transceivers compliant to the 100G SWDM4 MSA support reaches of 100 m when using OM4 fiber and 150 m when using OM5. These reaches are achieved even when using the worst-case combination of transmitter and fiber. For this work, 250 m reaches were chosen to allow for investigation of performance margin over the minimum supported distance. As demonstrated in Section IV, the OM4 fibers could not support error-free performance at 250 m for some wavelengths, so examining longer reaches could have been less informative. Margin measurements were carried out over 24 left-tilt OM4 and 24 OM5 dual-link channels consisting of concatenated 150 m and 100 m cables. We demonstrate that the OM5 channels support all four wavelengths with >5 dB of margin whereas post-FEC error-
free performance is not possible with the OM4 channels. To further characterize these fibers, 6 left-tilt OM4 fibers and 12 OM5 fibers taken from the same spools as the fibers used in the margin measurements were used in DMD measurements as well as sensitivity measurements. Most of the OM5 fibers have a left tilt whereas 2 have a right tilt at 850 nm. For the left-tilt OM4 fibers the longest wavelength channels limit the performance due to EMB values that are too low at 953 nm [19]. We demonstrate that EMB at 953 nm is a better indicator of long wavelength channel performance than an 850 nm bandwidth augmented by a DMD tilt metric.

OM5 fibers from the same spools were further characterized and used in the sensitivity measurements detailed in Section III B.

The EMB of these six OM4 fibers as a function of wavelength was measured using the DMD technique in compliance to FOTP-220 and is plotted in Fig. 2 from 840 through 953 nm. Each of the OM4 fibers selected for this study exhibited a bandwidth peak near 860 nm. In addition, each of the OM4 fibers is compliant to the OM4 and OM5 standards at 850 nm, but they exhibit EMB values lower than allowed by the OM5 standard at 953 nm, excluding them from OM5 compliance.

EMB vs. wavelength for the 12 OM5 fibers is shown in Fig. 3. Each of these fibers is compliant to the OM5 standard at both 850 and 953 nm. All but two of these fibers have a higher bandwidth at 880 than 850 nm, which corresponds to a left tilt. The remaining two fibers (Fiber 1 and Fiber 7) have higher bandwidth at 850 than 880 nm suggesting a right tilt. For these OM5 and OM4 fibers, EMB values at 850 and 953 nm are listed in Table I.

II. FIBER BANDWIDTH

For this work, 24 fibers that were OM5 compliant and 24 fibers that were only OM4 compliant were tested. Each of the OM4 fibers and most of the OM5 fibers were left-tilt at 850 nm. Example DMD plots from an OM4 fiber and an OM5 fiber are shown in Fig. 1. Each of these 48 fibers were used to construct dual-link channels used in the margin measurements described in Section III A, and 6 left-tilt OM4 fibers and 12

**TABLE I**

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>EMB @ 850 nm (MHz*km)</th>
<th>EMB @ 953 nm (MHz*km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left-Tilt OM4 Fiber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8826</td>
<td>2072</td>
</tr>
<tr>
<td>2</td>
<td>7328</td>
<td>2130</td>
</tr>
<tr>
<td>3</td>
<td>10077</td>
<td>2160</td>
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<tr>
<td>4</td>
<td>5055</td>
<td>2292</td>
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<tr>
<td>5</td>
<td>8592</td>
<td>2414</td>
</tr>
<tr>
<td>6</td>
<td>10238</td>
<td>2039</td>
</tr>
<tr>
<td>OM5 Fiber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8443</td>
<td>3182</td>
</tr>
<tr>
<td>2</td>
<td>5354</td>
<td>2763</td>
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<tr>
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<td>4402</td>
</tr>
<tr>
<td>4</td>
<td>6775</td>
<td>4034</td>
</tr>
<tr>
<td>5</td>
<td>5429</td>
<td>5569</td>
</tr>
<tr>
<td>6</td>
<td>5609</td>
<td>4034</td>
</tr>
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<td>8555</td>
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<td>4723</td>
<td>3716</td>
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<tr>
<td>11</td>
<td>6164</td>
<td>4850</td>
</tr>
<tr>
<td>12</td>
<td>5468</td>
<td>5875</td>
</tr>
</tbody>
</table>

Fiber tilt is better visualized in Fig. 4 (OM4) and Fig. 5 (OM5) where the peak of each DMD trace is plotted with
Fig. 4. DMD pulse peaks for different radial positions for 6 left-tilt OM4 fibers at (a) 850 nm and (b) 953 nm. Each of these fibers has a left tilt at 850 nm.

radial position for measurements taken at (a) 850 nm and (b) 953 nm. For both the left-tilt OM4 and the OM5 fibers the DMD traces have some structure, especially at 850 nm. The DMD pulse peaks can sway to the right or the left. This structure, present in real fibers, makes it difficult to quantify fiber tilt as the tilt can change directions depending on which subset of DMD traces is chosen. It has been proposed that the peak position of a subset of DMD traces like 5 µm and 19 µm [12, 15, 20] can be used to characterize fiber tilt. Each of the fibers represented in Fig. 4 have a left tilt when comparing the traces at 5 µm and 19 µm. They all tilt up and towards the left up to about 20 micrometers of radial offset.

As seen in Fig. 5, ten of the OM5 fibers have a left tilt at 850 nm when comparing the traces at 5 µm and 19 µm. The remaining two (Fiber 1 and Fiber 7) have a right small right tilt, comparing the traces at 5 µm and 19 µm, and were the only fibers which had higher EMB at 850 nm than at other wavelengths. In both figures, the absolute time is unimportant. Only the change, or differential, time is needed to characterize each fiber.

These fibers were selected to represent a range of interesting EMB values, not due to their erratic tilt. Table 1 lists the EMB at 953 nm for the 6 OM4 fibers and the 12 OM5 fibers. The OM4 fibers have a range of 2039 – 2414 MHz·km. These fibers represent a range of fibers that are 1) compliant to OM4 2) have a bandwidth peak greater than 850 nm, and 3) are not compliant to OM5. One OM4 fiber (fiber 4) has an EMB at 953 nm of 2414 MHz·km which is close to the OM5 requirement of 2470 MHz·km. The OM5 fibers have EMB values in the range from 2478 to 5875 MHz·km. While many have a high EMB, OM5 fiber 9 barely passed that standard with an EMB of 2478 MHz·km.

System performance also depends on chromatic dispersion. The relationship between modal and chromatic dispersion is complicated and depends on the interaction of the transmitter and fiber modes [10-16]. The chromatic dispersion properties of these fibers were not measured.

As seen in Section IV, the system performance at long wavelengths depends on EMB, not on the fiber tilt at 850 nm.
III. EXPERIMENTAL SETUP

A. Margin Measurements

The experimental setup for margin measurements is illustrated in Fig. 6. Four 100G SWDM4 transceivers were available for testing and were compliant to the 100G-SWDM4 MSA [7] which supports link lengths up to 100 m over OM4 and 150 m over OM5. One transceiver was used to transmit and the other used to receive. An Ethernet tester was used to generate the PRBS 2^23-1 pattern and apply forward error correction (FEC). The FEC limit was a BER of 5e-5. Double link channels of 250 m were constructed using 100 m and 150 m 12-fiber trunk cables (made from cable cut from the same reel) and 4 LC to MPO modules interconnected with short LC patch cords. Two trunks of each length from different cable reels were available for a total of 24 different fibers. Therefore, each constructed channel may or may not have used fiber from the same preform, depending on the combination used. A variable attenuator was inserted in the path to aid in measuring margin and sensitivity. For each measurement, the margin reported was the maximum added attenuation possible without any reported post-FEC errors in a 2-minute measurement window. The margin of 24 channels using OM5 fiber and 24 channels using left-tilt OM4 fiber was measured.

Fig. 6. Experimental setup for 100G SWDM margin measurements over 250 m double link channel. Either OM5 or left-tilt OM4 fiber was used.

B. Sensitivity Measurements

For sensitivity measurements, a single transceiver was used in a loopback configuration with the variable attenuator placed before the receiver as illustrated in Fig. 7. Of the available transceivers, the one with the best sensitivity was chosen and used for BER measurements with both OM5 and left-tilt OM4 fibers. In this case the 250 m links were formed by 250 m long continuous fibers. The 12 OM5 fibers and 6 OM4 fibers listed in Table I were tested in this configuration. BER was measured as a function of the received power for each wavelength channel reported by the transceiver. For reference, a “back-to-back” (BtB) measurement was performed with the same transceiver.

IV. EXPERIMENTAL RESULTS

A. Margin Measurements

We first measured the link margin above the FEC threshold using 250 m double link channels. All 24 OM5 and 24 left-tilt OM4 channels were measured with eight combinations of transmitter receiver pairs. For the 24 OM5 channels tested, the experimental results are shown in Fig. 8. The margin for each of the 24 channels is shown with different symbols for each transmitter/receiver combination. There was a total of 8 transmitter/receiver combinations tested. The minimum margin measured was 5 dB and the maximum was 11.25 dB. As expected, the channel performance depended on the combination of transmitter and fiber used [13-18].

None of the 24 left-tilt OM4 channels demonstrated error-free performance with any transceiver combination, meaning their margins were negative and therefore not plotted.

B. Sensitivity Measurements

To investigate why the left-tilt OM4 channels were unable to support error-free performance, sensitivity curves were obtained for 12 OM5 fibers (Fig. 9) and 6 left-tilt OM4 fibers (Fig. 10) using fibers from the same spools as the fibers used in the margin measurements with a single transceiver in a loopback configuration and compared to “back-to-back” (BtB). The fiber lengths were 250 m. The BER vs. received power results were plotted by wavelength channel. For the OM5 fibers, 880 nm showed the lowest power penalty whereas on average 850 nm showed the highest. One OM5 fiber showed an error floor at 940 nm less than 1e-7 which is below the FEC threshold of 5e-5 and therefore correctable. For this transceiver, each of the 12 fibers is capable of supporting error free performance post-FEC at all wavelengths at 250 m.

For the left-tilt OM4 fibers shown in Fig. 2 the performance varied drastically with wavelength as seen in Fig. 10. Channels at 850 and 880 nm showed little power penalty. The power penalty at 850 nm was lower for the OM4 fibers than the OM5 fibers. However, at longer wavelengths error floors were present for the 6 fibers. Of the OM4 fibers, Fiber 2 had the worst performance in that sync loss was observed at 910 and 940 nm for all received powers, so no data could be
captured. At 940 nm the noise floors for Fiber 1 and Fiber 3 appear to be below the FEC threshold of $5 \times 10^{-5}$. While the BER averaged over the 2-minute window was below the FEC limit, the instantaneous BER fluctuated above the FEC limit and would lead to uncorrected errors. The time-varying aspect of the BER can be observed in the way the BER curves seem to “oscillate” with received power. Despite the left tilt at 850 nm, none of the OM4 fibers were capable of supporting 100G SWDM transmission over 250 m due to lower bandwidth at longer wavelengths, consistent with the margin measurements in Section IVA.

Interaction of OM5 fibers with the SWDM transmitter determines the maximum supportable link length. The OM5 fibers and transceivers used in the work all supported 250 m links. The SWDM transceivers using OM5 links are rated to support a worst-case reach of 150 m. The longest possible reach is beyond the scope of this work.

As previously mentioned, EMB for each of the 12 OM5 and 6 left-tilt OM4 fibers was measured at 850 and 953 nm. The BER at a per channel received power of -12 dBm for each fiber is plotted in Fig. 11 for each of the four wavelengths vs. EMB measured at 850 nm. Whereas BER decreases with increasing EMB at 850 nm, there is no clear relationship between EMB at 850 nm and the BER at the other wavelengths. At 880 nm BER appears to be independent of EMB at 850 nm, and BER appears to increase with EMB at 850 nm for the two longest wavelength channels. The OM4 fibers all exhibited higher BERs at 910 and 940 nm despite the high EMB values and left tilt at 850 nm. This indicates that the EMB and tilt measured at 850 nm is a poor indicator of channel performance at these longer wavelengths.
Fig. 10. Experimental results for 100G SWDM over 6 left-tilt OM4 fibers of length 250 m at (a) 850, (b) 880, (c) 910, and (d) 940 nm. Error-free performance is not supported at 940 nm. Fiber 2 showed sync loss at 910 and 940 nm for all received powers.

Fig. 11. BER at (a) 850, (b) 880, (c) 910, and (d) 940 nm as a function of the EMB measured at 850 nm for the 6 left-tilt OM4 and 12 OM5 fibers used in sensitivity measurements.

The BER for the four wavelength channels vs. EMB at 953 nm is plotted in Fig. 12. As expected, for the 850 and 880 nm channels BER is flat with EMB at 953 nm. At these
wavelengths, the EMB at 850 nm is much more important. For the 910 and 940 nm channels, there is a clear relationship between BER performance and EMB at 953 nm. As seen in the figure, there was a trend where higher values of EMB correlate with lower measured BER. Since the left-tilt OM4 fibers do not have sufficient EMB at the longer wavelengths, the 910 and 940 nm channels had high BER and limited the total system reach.

![Figure 12](image.png)

Fig. 12. BER at (a) 850, (b) 880, (c) 910, and (d) 940 nm as a function of the EMB measured at 953 nm for the 6 left-tilt OM4 and 12 OM5 fibers used in sensitivity measurements. In (c) and (d) the two right-tilt OM5 fibers are circled.

In Fig. 12 (c) and (d) the two right-tilt OM5 fibers are circled. At both 910 and 940 nm the right-tilt OM5 fibers outperformed the 6 left-tilt OM4 fibers. This indicates that EMB at 953 nm is a better indicator of long wavelength channel performance than the DMD tilt at 850 nm.

V. CONCLUSIONS

We investigated 100G SWDM transmission over 250 m OM5 and left-tilt OM4 multimode fiber. We demonstrated that the 250 m dual link OM5 channels had superior performance with over 5 dB margin whereas the OM4 channels were not able to achieve error-free performance. We showed that performance of the 250 m continuous OM4 fibers was limited by the longest wavelength channels due to low fiber bandwidth at longer wavelengths. The OM4 fibers had a left tilt at 850 nm, but they performed worse than the OM5 fibers, even those with a right tilt. We conclude that by specifying bandwidth over a range of wavelengths, OM5 fiber can ensure greater operating margin and longer reach SWDM links than left-tilt OM4 fiber.

REFERENCES


