O-band Transmission over High-Cutoff G.654.C Fiber

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Abstract: We demonstrate via modeling and experiments the feasibility of O-band transmission over ultra-low loss G.654.C fiber in cabled conditions. Lab experiments with a 100G O-band transceiver show no penalty and transmission up to 99 km. © 2023 The Author(s)

1. Introduction

O-band transmission over single-mode fiber in the 1300 nm region is widely used in data centers (DCs) with intensity-modulated direct detection (IMDD) transceivers. Intra-DC links are typically 2 km or less. Longer reach versions of these transceivers are also used for low-cost DC interconnection (DCI) and metro transmission for links from 10 km (100GBASE-LR4) up to 80 km (100GBASE-ZR4). Fiber used for O-band transmission in both intra-DC and DCI/metro applications is conventionally G.652-compliant standard single-mode fiber with cable cutoff (CC) typically specified as less than 1260 nm, ensuring single-mode operation for O-band systems, which usually have laser wavelengths in the 1270-1330 nm range. G.652-compliant optical fibers are usually manufactured with Germanium-doped cores and may have attenuation specifications at 1310 nm and 1550 nm of about 0.35 dB/km and 0.20 dB/km. On the other hand, ultra-low loss silica-core fibers with nominally the same 1550 nm effective area (~80 μm^2) and zero-dispersion wavelength (~1310 nm) but significantly lower attenuation (<0.16 dB/km at 1550 nm) are widely deployed in terrestrial long-haul systems for C-band transmission. Because of the different core material, the attenuation reduction compared to Ge-doped fibers extends to the O-band and can offer longer system reach because of the lower O-band attenuation. An example of this fiber type is G.654.C-compliant Corning® SMF-28® ULL optical fiber. However, one significant difference implied by the G.654.C standard is a CC limit of 1530 nm [1]. Because of the higher CC allowance, such ultra-low loss G.654.C fibers have not been historically used for O-band transmission.

In this work, we demonstrate the feasibility of O-band transmission over the highest cutoff SMF-28 ULL fiber when deployed in conditions representative of terrestrial outside plant cables. We model the higher order mode attenuation (LP_{11} mode) for bend diameters representative of maximum diameter conditions in loose-tube cables. We then calculate expected levels of multipath interference (MPI) for transmission in DCI/metro links considering splice losses, splice lengths, fiber LP_{11} mode attenuation in the cabled fiber and in splice trays, and estimated mode coupling strength [2-5]. We find that the expected MPI penalty is negligible in cable conditions for IMDD signals, even for links comprised completely from fibers with the highest cutoff. Finally, we conduct transmission experiments with a 100G O-band transceiver rated for 80 km transmission and demonstrate transmission exhibiting no effects from MPI over the G.654.C fiber and link lengths up to 99 km.

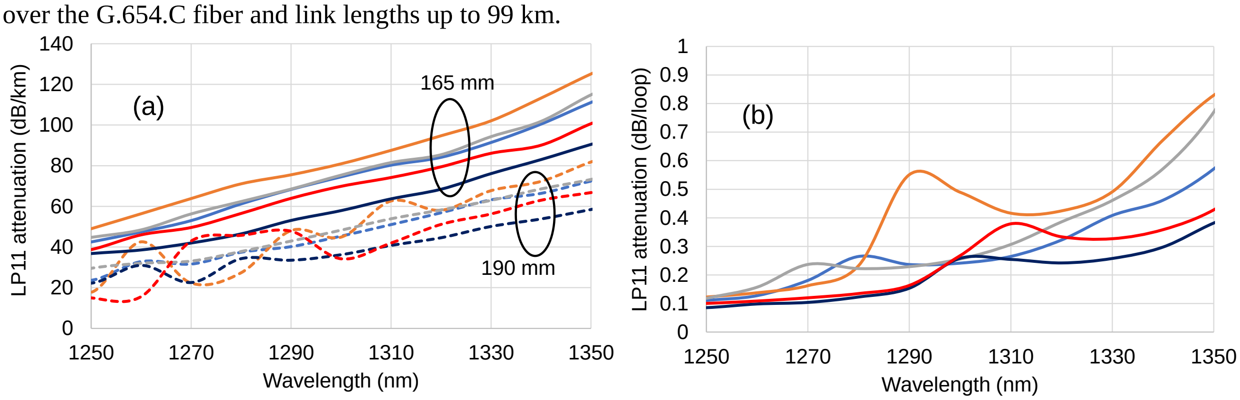

Fig. 1: LP_{11} mode attenuation results for 5 high-cutoff G.654.C fibers. a) Bend conditions of cable deployment, b) bend condition of 80 mm loops experienced in splice trays. The same colors represent the same fibers in the different cases.

2. Higher order mode attenuation and MPI modeling

We began the study by identifying specific spools of SMF-28 ULL fiber with the highest measured CC values in the manufacturing distribution. We note that the manufacturer's maximum CC limit for this fiber product is 1520 nm. We selected 5 spools with the highest cutoff values, all of which were in the 99th percentile or higher and greater than

1450 nm. The average CC of the manufacturing distribution is about 1300 nm. The refractive index profile of each fiber was then modeled using a beam propagation method [6] to calculate the attenuation of the higher order LP_{11} mode for different bend diameters. The LP_{11} mode attenuation was calculated over a wide wavelength range including the O-band. The bend conditions modeled were straight-line and bend diameters of 80, 165, and 190 mm. The 80 mm bend diameter corresponds to the approximate fiber loop diameter experienced in splice trays, and the 165- and 190-mm bend diameters correspond approximately to maximum fiber bend conditions expected in different loose-tube cable configurations. The results of the LP_{11} attenuation modeling are shown in Fig. 1 as a function of wavelength in a region encompassing the normal O-band transmission range of 1270-1330 nm. Note that for the larger diameter bends (cable deployment) the LP_{11} attenuation is given in units of dB/km while the results for the 80 mm bend is expressed in units of dB/loop since it represents the higher order mode loss in a splice tray.

To estimate the MPI produced in a DCI/metro span, we modeled the system illustrated schematically in Fig. 2. For typical terrestrial deployment, we assumed splice points in the cable every 5 km. The splices are in splice trays with several 80 mm loops of fiber on each side of the splice. We assumed 4 loops on each side here. The average splice loss was assumed to be 0.05 dB with a small random variation around this average. Conservatively, any loss L_{splice} of the fundamental mode at the splice point was modeled with the lost power being fully transferred to the higher order mode with coupling coefficient $\varepsilon = 1 - 10^{(-L_{splice}(dB)/10)}$ and any power already in the LP_{11} mode coupled back into the fundamental LP_{01} mode with the same coefficient [3-5]. The fiber in the cable was modeled with bend diameters of 165 or 190 mm to evaluate the sensitivity to this parameter with representative values.

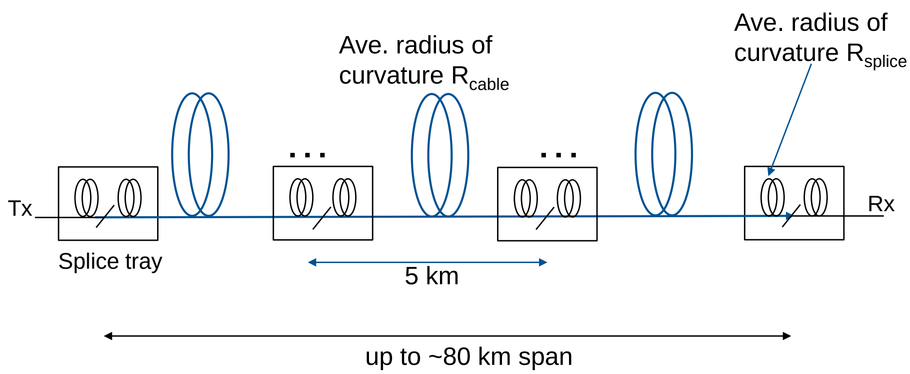

Fig. 2: Schematic illustration of DCI/metro link modeled to estimate MPI level.

To model the MPI level for a link as in Fig. 2, necessary parameters are splice loss, fiber LP_{11} attenuation for the bend conditions experienced, and the power coupling coefficient expected during fiber transmission [2-5]. To estimate the distributed coupling coefficient κ, we measured the MPI of several long lengths comprised of the high cutoff fiber on shipping spools by analysis of the power fluctuations of a CW laser transmitted through the fiber [5,7]. Using the measured MPI and calculated LP_{11} attenuation values in Fig. 1a for 165 mm bend diameter, which is the same as the inner diameter of fiber on a shipping spool, we estimated the coupling coefficient during propagation in the range of 0.002-0.004 km^{-1}. We then chose the value of 0.004 km^{-1} to use in the MPI modeling of a link including splices with these fibers representing the highest CC values found in the fiber distribution.

To understand the impact of different factors governing MPI generation in a link, we calculated the MPI according to the model described in [2,3,5] for different configurations. The results are shown in Fig. 3 for the cases of 1) purely straight-line deployment with no loops surrounding the splices, 2) purely straight-line including 4 loops of 80 mm diameter on each side of the splices, 3) cable deployment with 165 mm bend diameter including loops in splice trays, and 4) cable deployment with 190 mm bend diameter including splice tray loops. The cases with straight-line deployment are not realistic or representative of real cable conditions. The results in Fig. 3a are for a span of length 80.7 km comprised of 3 SMF-28 ULL fiber spools with average CC of 1472 nm, and Fig. 3b shows results for an 80 km span if comprised completely of the fiber with the highest CC in our set (~1490-1500 nm). Thus, the results in Fig. 3 show predicted MPI results that correspond to worst-case conditions with the full span being constructed with fiber having CC in the 99th percentile or higher. The results are given as MPI (dB) per span as a function of wavelength. There is only small variation with wavelength in general and the maximum MPI under cable conditions is about -33 to -34 dB for 80 km spans at 1270 nm. This level of MPI would produce power penalties for NRZ and PAM-4 signals at BER = $1x10^{-6}$ with randomly polarized interference terms < 0.03 dB and < 0.2 dB, respectively [8-11]. Therefore, even worst-case MPI effects on system performance should be negligible. Realistic conditions in practical cable deployments will have even smaller MPI given the extreme outlying nature of these fibers in terms of the CC manufacturing distribution.

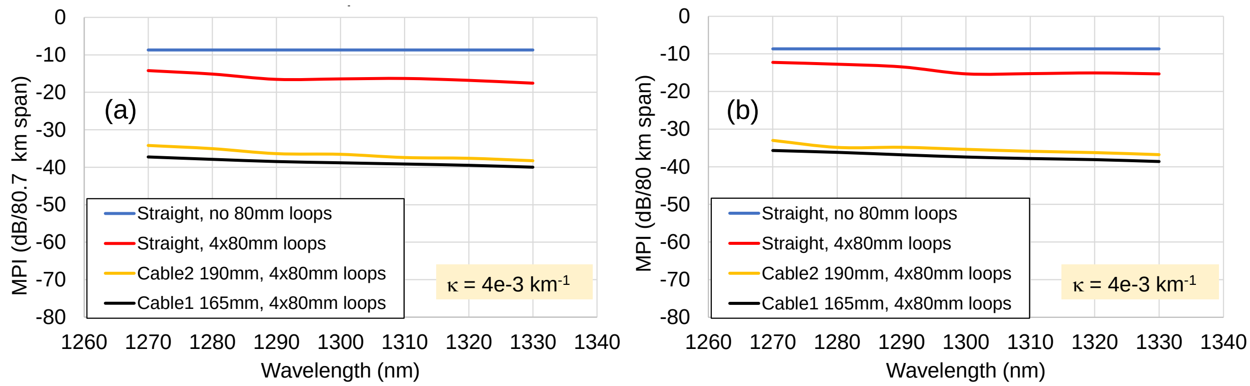

Fig. 3: MPI per span as a function of wavelength in the O-band. a) 80.7 km span comprised of 3 spools of fiber with average CC 1472 nm. b) 80 km span comprised completely of fiber with highest CC ~1500 nm.

3. Experimental Transmission Results

After modeling, we constructed spans from the high-cutoff G.654.C fiber spools and measured transmission performance using a commercial 100G O-band transceiver. The transceiver was a 100GBASE-ZR4 module rated for 80 km transmission (Model: QSFPTEK QT-QSFP28-ZR4). It employed 4×25.78 Gbaud NRZ signals on four wavelengths in the range of 1295-1310 nm (LWDM wavelength plan). For comparison, we transmitted the same signal over G.652 fiber with CC <1260 nm. Fig. 4 has results of pre-FEC BER vs. received power (controlled by a VOA at the receive end) and shows no penalty from MPI for the G.654.C fiber. Error-free transmission after KR4 FEC was attained over the high cutoff SMF-28 ULL fiber up to 99 km with a power margin of more than 7 dB at the pre-FEC BER of $1x10^{-5}$. Including splices and connectors, the average O-band span loss of the SMF-28 ULL fiber was 0.28 dB/km while that of the G.652 fiber was 0.34 dB/km. Transmission over both fiber types exhibited better performance than in back-to-back likely due to favorable interaction of laser chirp with fiber dispersion [12].

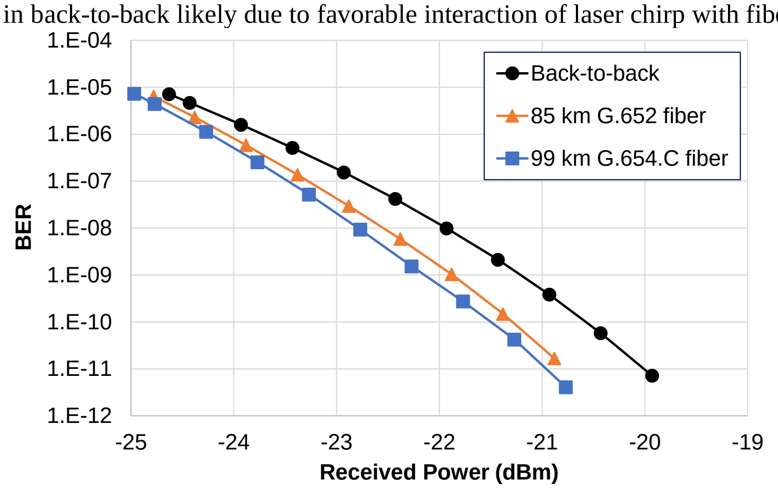

Fig.4: Experimental transmission results with a commercial 100G O-band transceiver.

4. Summary and Discussion

We demonstrated via modeling and experiments that O-band transmission through G.654.C fiber with high CC is feasible with negligible MPI penalty in loose tube cable deployment conditions. 100G-ZR transmission over 99 km of ultra-low loss high-CC G.654.C fiber demonstrated no penalty using an 80 km rated transceiver with more than 7 dB power margin. Ultra-low loss G.654.C fibers can enable higher data rates and/or longer link distances for DC, FTTx, or DCI systems with O-band IMDD signals. These results suggest that dual purpose cables with the same advanced fiber may be used for both long-haul and FTTx systems with advantaged performance in both system types.

5. References

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