On the Feasibility of S-band Transmission over G.654.E Fiber

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Abstract *We investigate the performance of S-band transmission over a G.654.E optical fiber with cable cutoff up to 1520 nm. Modeling of higher order mode attenuation and MPI generation in representative cable deployment bend conditions demonstrates negligible impairment from MPI in realistic conditions.*

Introduction

As long-haul (LH) data traffic growth continues to grow rapidly, the optical communications industry continues to look for ways to increase the transmission capacity of optical fibers. Spectral efficiency (SE) has increased dramatically in the era of coherent transmission, but this has largely saturated and is not likely to increase significantly further [1]. In this context, one approach to increase fiber capacity is by increasing the number of spatial paths such as in multi-core fiber (MCF) or mode-division multiplexing in few-mode fiber (FMF) or multimode fiber (MMF) [2-5]. Another means for achieving fiber capacity increase is to transmit signals over wider optical bandwidths in single-core single-mode fibers [6,7]. This approach has the benefit of using conventional optical fiber with a well-established ecosystem and practices. Dense wavelength division multiplexing (DWDM) transmission over the C-band of erbium-doped fiber amplifiers (EDFAs) is of course the standard for LH transmission systems now, with some system operators moving to also use L-band transmission to essentially double fiber capacity [8]. After the L-band, the next logical wavelength band for LH transmission systems is the S-band, and S+C+L ultra-wideband (UWB) transmission systems are gaining research attention [9-11] as amplification options for the S-band mature [12].

To date, most UWB research has assumed the use of optical fibers with cable cutoff below the S-band such as G.652-compliant fibers. For the purposes of this work, we assume the S-band to cover the range of about 1450-1520 nm. However, a significant impairment suffered in UWB systems is stimulated Raman scattering (SRS) in which optical power is transferred from the S-band to the C-band and L-band. The adverse effects of SRS can be significantly reduced using optical fibers with larger effective area (e.g. G.654.E fibers) that increase tolerance to optical nonlinear effects such as SRS [11]. Most consideration for UWBs systems has been given to G.652 fiber since its cable cutoff (CC) is ≤1260 nm and no issue of multipath interference (MPI) arises for S-band transmission. On the other hand, G.654.E fibers offer increased nonlinear tolerance as well as lower attenuation in many cases [13,14] but the G.654.E standard allows CC up to 1530 nm [15]. In this work, we address for the first time the question of S-band transmission in a commercially available G.654.E fiber and demonstrate via modeling that S-band transmission is very feasible with negligible expected impairment from MPI.

G.654.E Optical Fiber and its Characteristics

The optical fiber considered for this study is Corning® TXF® optical fiber. It is a G.654.E-compliant fiber with nominal attenuation at 1550 nm of 0.166 dB/km and effective area of 125 μm^2. The larger effective area and lower attenuation of this fiber was found to enable 18% greater UWB transmission capacity compared to standard single-mode fiber in a previous study [11]. However, the potential effects of MPI in the S-band were not evaluated in [11]. As a G.654.E-compliant fiber, the cable cutoff can be up to 1530 nm, although we note that the manufacturer's upper limit for CC is 1520 nm.

For this study, we searched through the fiber manufacturing CC distribution statistics to identify three fiber samples with CC at the extreme upper end of the distribution. These fibers all had measured CC values of at least 1510 nm or higher and were in the 99th percentile or higher of the CC distribution. We then modeled the refractive index profiles of the fibers using a beam propagation method [16] to calculate the attenuation of the higher order LP_{11} mode as a function of wavelength for a range of wavelengths below CC in the S-band. The LP_{11} attenuation was calculated for different bend conditions including straight-line and bend diameters of 80 mm, 165 mm, and 190 mm. The 80 mm diameter corresponds to the approximate loop diameter experienced in splice trays as well as the condition for CC measurements, while 165 mm and 190 mm diameters represent the approximate maximum bend conditions expected in different loose-tube cable deployment configurations. The measured and modeled CC values were within 5 nm for each fiber. Calculated LP_{11} attenuation values for the fibers in a straight-line condition, 165 mm bend diameter (cable condition), and 80 mm bend diameter are shown in Fig. 1. The 80 mm bend results are given in units of dB/loop while the others are in dB/km.

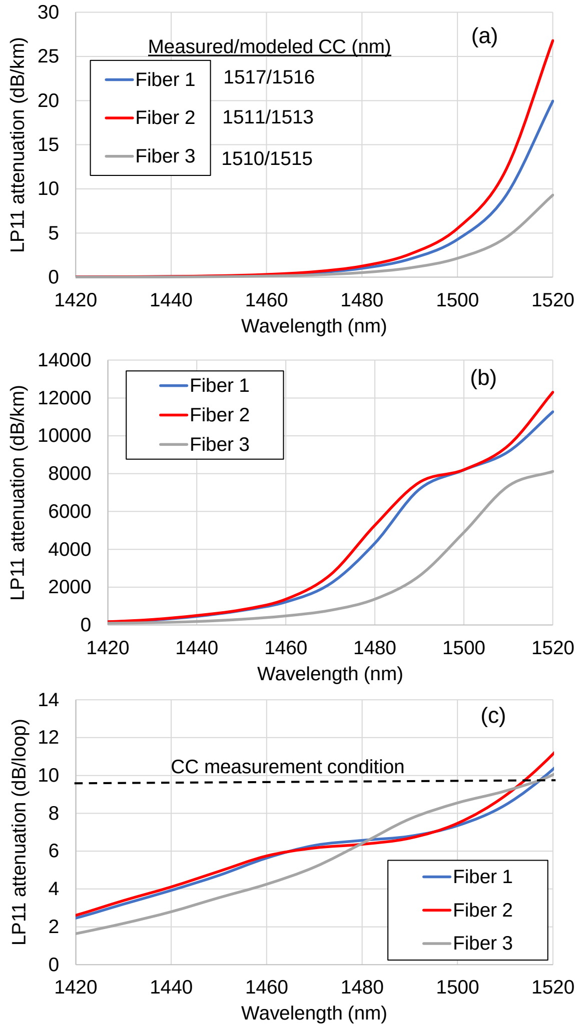

Fig. 1: LP_{11} attenuation in 3 high-cutoff fibers for a) straight-line, b) 165 mm bend diameter, c) 80 mm bend diameter.

For a continuous length of fiber with propagation below cutoff, the main two parameters that govern the growth of MPI during propagation are the distributed power coupling coefficient κ and the differential mode attenuation (DMA) defined as the excess higher order mode (LP_{11}) attenuation relative to the fundamental mode [17,18]. When the DMA is high, defined as $\Delta\alpha^2 >> 4\kappa^2$, then the MPI can be calculated as

$$MPI = \frac{\kappa^2 L}{\Delta\alpha} \quad (1)$$

where $\Delta\alpha$ is the DMA given in linear units /km, L is the fiber length, and κ is also in units of /km. MPI is defined here as the ratio of the total power of interfering terms to the fundamental signal power at the output of a span, akin to crosstalk in MCF. These interfering terms are generated by signal light that couples from the fundamental to a higher order mode, propagates for some distance, and then couples back to the fundamental mode with a delay because of the difference in the propagation constants. We calculated the DMA from the LP_{11} attenuation from the index profiles as shown in Fig. 1. In order to estimate the coupling coefficient κ, we first made MPI measurements and used the predicted DMA according to Eq. 1. The MPI measurements [18,19] were made on two of the three high-cutoff fibers loaded onto 370 mm diameter measurement spools to have low enough DMA that the MPI would be measurable over a ~50 km fiber length. The results of the coupling coefficient calculations from these measurements over the range from 1400-1480 nm are shown in Fig. 2. It was not possible to obtain accurate MPI data above 1480 nm because the results were at the level of back-to-back results limited by the noise floor of the measurements. The average κ value was determined to be about 7×10^{-4} /km.

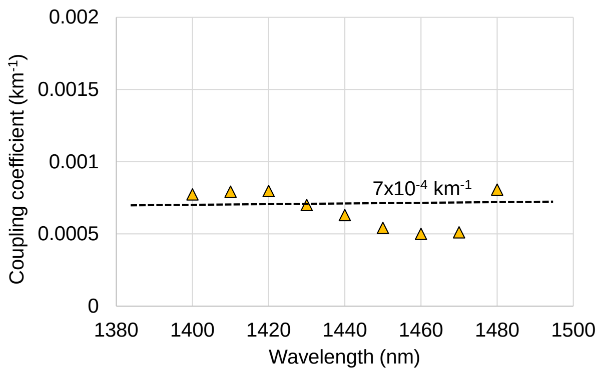

Fig. 2: Fiber coupling coefficient calculated from MPI measurements and LP_{11} attenuation predictions.

MPI modeling of S-band Transmission

Of these three fibers at the extreme upper end of the CC distribution, Fiber 3 shows the lowest S-band LP_{11} attenuation behaviour in Fig.1 and would thus be the most likely to promote MPI

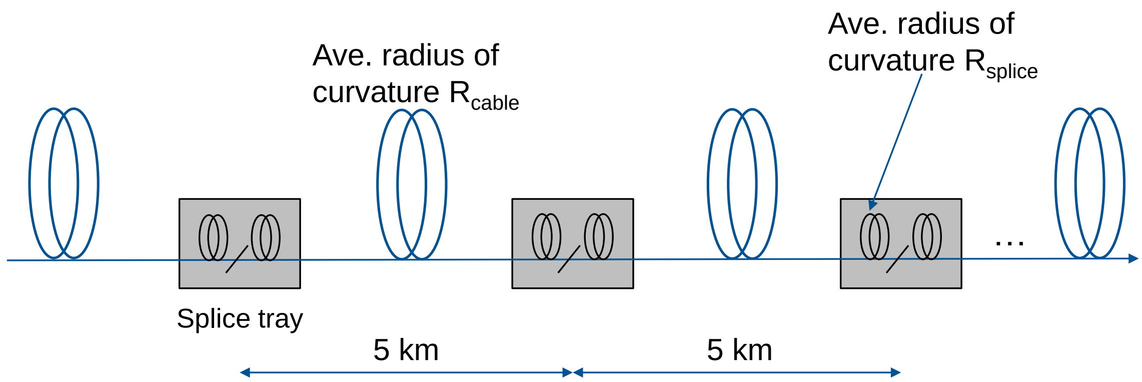

Fig. 3: Schematic diagram of an optical span comprised of 5 km sections with splices between each section.

growth and performance impairment from MPI. We therefore chose to use this fiber as a worst-case example to model potential MPI generation in LH terrestrial systems. An illustration of a modeled span is shown in Fig. 3. The distance between splices was 5 km with an average splice loss of 0.05 dB. The general parameters of the MPI modeling are given in Table 1. To be conservative, we modeled a κ value more than double the estimated value from the MPI measurements. We also assumed that the discrete coupling coefficient from LP_{01} to LP_{11} at splice points represented the full amount of loss, and that light in the LP_{11} mode coupled back to LP_{01} with the same coefficient given by

$$\varepsilon = 1 - 10^{-L_{splice}/10} \qquad (2)$$

where L_{splice} is the splice loss in dB.

Table 1: MPI System Modeling Parameters

Parameter	Value
R_{cable} (mm)	82.5, 95
R_{splice} (mm)	40
#loops on each side of a splice	4
Splice loss to self (dB)	0.05
Splice loss to G.652 fiber at span ends (dB)	0.2
Coupling coef. κ (/km)	1.5×10^{-3}

Results of the MPI modeling are given in Fig. 4. We modeled four conditions corresponding to purely straight-line deployment with splices but no fiber loops in splice trays, straight-line deployment including the fiber loops in the splice locations, 190 mm bend diameter (cable condition) including splices and loops, and 165 mm diameter (another cable condition) including splices and loops. The MPI results are given in units of dB/km, and the x-axis is the wavelength relative to CC. If CC = 1520 nm, then -70 nm relative to that is 1450 nm and at the far blue end of the S-band. We observe that at this relative wavelength (i.e. 1450 nm), the expected level of MPI in cabled conditions is less than -70 dB/km, and is even smaller for longer wavelengths. Similar to crosstalk, this level of distributed MPI would produce an SNR penalty significantly less than 0.1 dB for LH terrestrial systems [20,21].

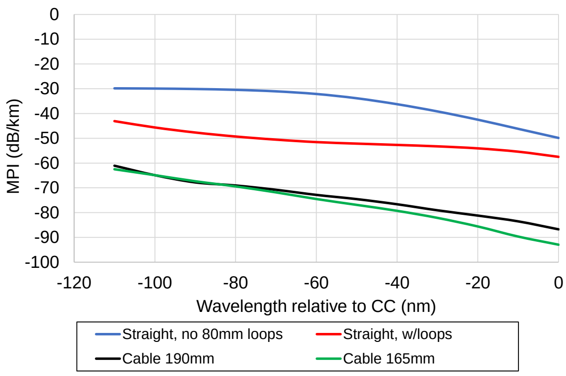

Fig. 4: MPI results as a function of wavelength below cable cutoff for four different deployment conditions.

Summary and Conclusions

We have modeled the deployment of a G.654.E fiber with CC up to 1520 nm for potential MPI generation in S-band transmission. We first evaluated three fibers in terms of higher order mode attenuation selected from the extreme upper end of the manufacturing distribution (at least 99th percentile) with measured cable cutoffs close to 1520 nm. We then modeled MPI generation in the fiber with the lowest LP_{11} attenuation and thus most likely to exhibit MPI during transmission. We found that even in a worst case where an entire link is comprised of this fiber, the expected MPI levels in the S-band in cabled conditions are below -70 dB/km and would result in negligible SNR penalty or capacity loss. In practice, real spans and links would be comprised of fiber sections representing the full cable cutoff manufacturing distribution and would therefore exhibit MPI generation levels far lower than this worst case modeled. The results strongly suggest that S-band transmission is feasible over this G.654.E fiber as deployed in cables without signal degradation from MPI.

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