MPI Measurements of Quasi-Single-Mode Fibers

John D. Downie, Jason Hurley, Ioannis Roudas, Konstantin Koreshkov*, and Michal Mlejnek
Corning Incorporated, 1 Riverfront Plaza, Corning, NY 14831, Email: DownieJD@Corning.com
*Corning Scientific Center, 26A Shatelena str., 194021, St. Petersburg, Russia

***Abstract*— We study four different measurement methods of multi-path interference (MPI) in quasi-single-mode (QSM) fibers and compare their consistency and accuracy. Three methods agree to within 1.7 dB in each case while one overestimates MPI.**

I. Introduction

MULTI-PATH interference (MPI) may result from single-mode transmission through quasi-single-mode, few-mode, and multi-mode fibers [1-4]. If the optical signal is launched into the fundamental mode, MPI arising from discrete or distributed mode coupling throughout the span can cause system performance degradation, and accurate characterization or estimation of the generated MPI is important. Here, we study four measurement methods of MPI produced in quasi-single-mode fibers with single-mode transmission. In two methods, the MPI estimates are based on system penalty. We first measure optical signal-to-noise ratio (OSNR) penalties for 256 Gb/s polarization multiplexed 16-quadrature amplitude modulation (PM-16QAM) signals in an MPI emulator. Transmission data through a QSM fiber span under test are compared to the emulator data as well as a Gaussian noise model to estimate the span MPI values. The other two methods are based on power fluctuations of a continuous-wave CW external cavity laser (ECL) launched into the QSM fiber spans [5, 6]. We find good agreement between the two transmission-based methods and the laser power approach evaluated statistically, but that use of the laser power maximum and minimum values overestimates the MPI.

II. MPI Emulator and Penalty Measurements

The first approach investigated for estimating the MPI induced in QSM fibers is based on the actual penalty incurred for single-mode transmission. Toward that end, we constructed an MPI emulator with which to measure such penalties for a discrete number of crosstalk terms [7,8]. Since MPI generated in a QSM fiber is expected to be distributed in nature, an objective of this approach was to understand how well the penalties induced in an emulator with discrete crosstalk terms correspond to the penalties observed during transmission through the fibers. The MPI emulator was built and tested with eight crosstalk terms. The experimental set-up is shown in Fig. 1(a). The definition of MPI used here is the ratio of the total crosstalk power of all terms to the main signal power,

$$\mathrm{MPI} = \sum_{i=1}^{N} P_{xt,i} / P_{signal}. \quad (1)$$

The ECL light was modulated at 32 Gbaud (256 Gb/s) using a PM-16QAM transmitter and split into two paths with the relative power levels controlled to set a given MPI level (defined as the ratio of the total crosstalk power to the main signal power). The relative path length differences between each crosstalk path and the signal path are illustrated in Fig. 1(a). The received OSNR level was controlled by a variable optical attenuator (VOA) in front of the receiver pre-amplifier. The signal bit error rate (BER) was measured as a function of OSNR for different MPI levels and the required OSNR to achieve a given BER, such as 10^{-3} or 10^{-2}, was determined as a function of MPI level. The states of polarization of the signal and the interferers were not controlled as the penalty was previously found essentially independent of this for PM signals [8]. The relative power levels of the eight crosstalk terms were within 2 dB of each other. The measured OSNR penalty results for the 256 Gb/s PM-16QAM signal are given in Fig. 1(b). The results show that MPI should be less than about -26 dB and -22 dB for ≤ 1 dB OSNR penalty at BER values of 10^{-3} and 10^{-2}, respectively.

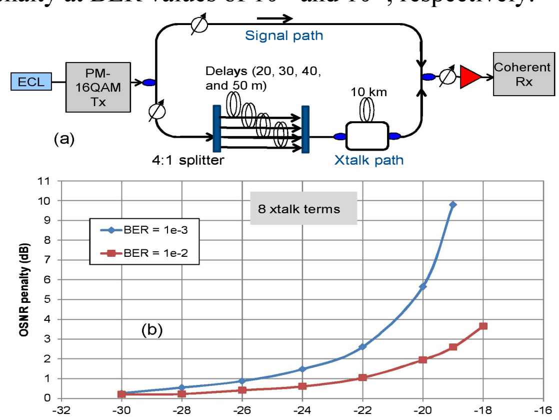

Fig. 1. (a) Experimental set-up for measurement of MPI penalties for 8 crosstalk terms. (b) OSNR penalties vs. total MPI.

III. Transmission through QSM Fiber Spans

Three different 154 km long QSM fiber spans were next used in transmission tests with the 256 Gb/s PM-16QAM signal. The spans were comprised of different spliced combinations of six reels of fiber, each 51.4 km long. The fiber supported the LP_{01} and LP_{11} modes, with slightly higher attenuation of the LP_{11} mode. The transmission experiments were conducted in the linear regime to avoid nonlinear effects. A channel at 1550.92 nm was launched into each span via a single-mode jumper spliced to the front of the span. Another single-

978-1-4799-7465-8/15/$31.00

mode fiber was spliced at the span end. MPI penalties are due to distributed mode coupling within the fiber as the signal launched into the LP_{01} mode couples out to LP_{11} mode and then couples back in to the fundamental before reaching the end of the span [2, 9]. OSNR was controlled with noise-loading and an example of the measured BER data vs. OSNR through a span and in back-to-back is shown in Fig. 2.

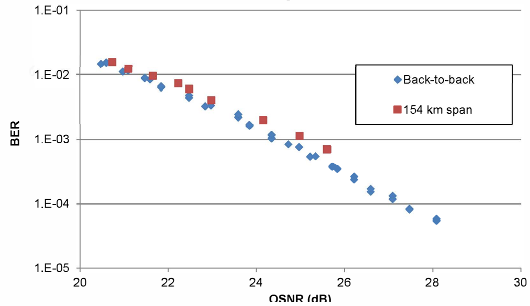

Fig. 2. BER vs. OSNR through a QSM fiber span and back-to-back.

The transmission data obtained were used to estimate the MPI generated in each span in two ways. First, the OSNR penalties observed at 10^{-3} and 10^{-2} BER such as in Fig. 2 were compared to the data taken with the MPI emulator with eight discrete crosstalk terms in Fig. 1(b). A second estimate was derived from the transmission data by adapting previous models relating OSNR penalty to overall MPI level for coherent systems [6,10]. The model assumes multiple interferers produce Gaussian noise with zero mean and variance σ^2_{MPI} as measured in the optical receiver bandwidth. Then an effective OSNR can be expressed as

$$\mathrm{OSNR}_{\mathrm{eff}} = P/(\sigma^2_{\mathrm{ASE}} + \sigma^2_{\mathrm{MPI,eq}}). \quad (2)$$

where P is the total average signal power, σ^2_{ASE} is the ASE noise power within the measurement resolution bandwidth $\Delta\nu_{res}$, and $\sigma^2_{\mathrm{MPI,eq}}$ is the power of a fictitious additive white Gaussian noise, also within $\Delta\nu_{res}$, that gives rise to the penalty from MPI. Note that the OSNR penalty produced by MPI assumes an ASE-like white noise spectrum while the actual crosstalk power has the spectrum of the signal and is filtered by the receiver optical bandwidth B. The equivalent MPI noise term in Eq. (2) is obtained by scaling the total crosstalk power as $\sigma^2_{\mathrm{MPI,eq}} = \Delta\nu_{\mathrm{res}}\sigma^2_{\mathrm{MPI}}/B$. The MPI is then found by

$$\mathrm{MPI} = (\mathrm{B}/\Delta\nu_{res})\left[OSNR_{eff}^{-1} - OSNR_{ASE}^{-1}\right] \quad (3)$$

In (3), $\mathrm{OSNR}_{\mathrm{ASE}}$ is the actual measured OSNR required for the system with MPI at a given BER, and $\mathrm{OSNR}_{\mathrm{eff}}$ is the corresponding OSNR in the back-to-back condition. Here, B = 0.32 nm and $\Delta\nu_{res}$ =0.1 nm.

IV. Power Fluctuation Measurements

In this approach, a CW ECL was launched into the fundamental mode of the QSM fiber via a single-mode fiber jumper, passed back into another single-mode jumper at the output, and detected with a power meter. We employed a continuously varying polarization scrambler before launch. The detector had an averaging time of 20 ms, and samples were captured every 0.25 sec for at least two hours. We investigated two means of using the captured data to estimate the MPI. In one method [5], the MPI is calculated from the difference between maximum and minimum power readings ΔP as

$$MPI(dB) = 20\log\left[\frac{10^{\frac{\Delta P(dB)}{20}} - 1}{10^{\frac{\Delta P(dB)}{20}} + 1}\right] \quad (4)$$

For the definition of MPI used here (1), the calculated MPI in (4) is accurate when there is a single crosstalk term present but should be high when there are multiple terms. If all terms were of equal strength and polarization aligned with each other and the signal, the MPI overestimation in dB would be 10log(N) but full realization of this condition is unlikely in practice. A second estimate of the MPI is obtained from the average power P_{ave} and standard deviation σ, assuming that signal and crosstalk terms are randomly polarized with respect to each other [6]. The MPI estimate is

$$MPI(dB) = 20\log[\sigma/P_{ave}]. \quad (5)$$

The results for the MPI estimates of the three 154 km QSM fiber spans are given in Fig. 3. The estimates from the CW laser power fluctuations using (4) (labeled Delta P) are high relative to the other methods. The other three methods agree to within about 1.7 dB in all cases, suggesting that the behavior of the MPI emulator with eight discrete crosstalk terms reasonably approximates the QSM fiber transmission, which can also be reasonably described by the Gaussian model.

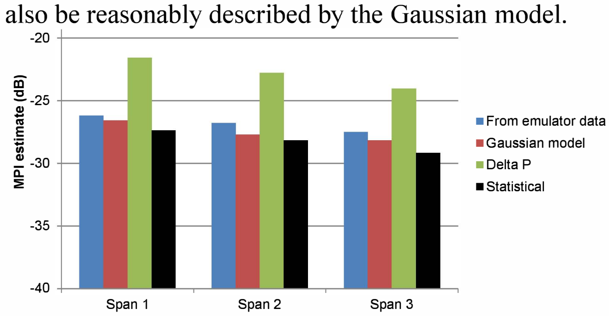

Fig. 3. Four MPI estimates of three 154 km QSM fiber spans.

V. Summary

We studied four methods to estimate the MPI induced by transmission in QSM fiber spans. The results from three methods are consistent. The higher estimate of the fourth approach confirms the MPI's distributed nature.

References

[1] F. Yaman et al., Optics Express 18, 21342-21349 (2010).
[2] N. Bai et al., Opt. Express 20, 24010-24017 (2012).
[3] J. D. Downie et al., Opt. Express 19, B363-B369 (2011).
[4] Q. Sui et al., OFC 2014, paper M3C.5 (2014).
[5] S. Ramachandran et al., IEEE PTL, 15, 1171-1173 (2003).
[6] W. Zheng et al., IEEE Trans. Inst. and Meas. 53, 15-23 (2004).
[7] L. E. Nelson et al., OFC 2009, paper OTuN3 (2009).
[8] P. J. Winzer et al., ECOC 2011, paper Tu.5.B.7 (2011).
[9] N. A. Kaliteevskiy et al., Opt. and Spect., 114, 913-916 (2013).
[10] K.-P. Ho, J. Lightw. Technol. 29, pp. 124-131 (2011).