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# Experimental Investigation of Coupling Offset Tolerances in a Space-Division Multiplexed 15-Mode Fiber Transmission System

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***Abstract*** *We investigate the coupling offset tolerances of a space-division multiplexed 15-mode fiber transmission system. Alignment offset of up to* 6 µm *can lower the Q-Factor by 6 dB for 16-QAM signals. Increased mode-dependent loss is identified as a key origin of the observed signal quality degradation.* *©2022 The Author(s)*

## Introduction

Space-division multiplexing (SDM) has been identified as a strong candidate to increase the per-fiber data rates in future optical fiber transmission systems[1] in order to support the continuing exponential demands for high capacity data communication. Various fiber types have been proposed for SDM transmission, including multi-core fibers (MCFs)[2] and few-mode fibers (FMFs)[3]. Both fiber types have been demonstrated to support high capacity optical transmission, with single-mode MCFs supporting more than 2 peta-bit/s[4], few-mode MCFs more than 10 peta-bit/s[5] and single-core FMFs with more than 1 peta-bit/s[6].

While increased data rates have shown the benefit of using novel SDM fibers, their usage comes at the cost of an increased handling complexity. This is maybe most notable for MCFs where the absence of full rotational symmetry demands a careful design of rotational connector tolerances[7],[8] and novel splicing procedures[9]. FMFs, on the other hand, have full rotational symmetry and can be spliced and connected with standard single mode fiber (SMF) components. However, unlike SMFs where a lateral splice offset leads to a lumped loss, splice points in FMF transmission can lead to unequal attenuation between fiber modes[10]. This increases the system's mode-dependent loss (MDL), reducing the transmission capacity of the transmission system beyond the impact of lumped loss[10],[11]. In contrast to previous theoretical studies that have investigated the system capacity reduction due to splicing offsets[10], we here experimentally investigate the signal quality degradation in a 15-mode FMF transmission system. We compare Q-Factors and MDL at coupling offsets between 0 µm and 6 µm in a back-to-back (B2B) scenario and after 15.2 km transmission using 24.5 GBaud 16-quadrature amplitude modulation (QAM) signals. We show that coupling offsets impact higher order modes more severely than lower order modes. This is attributed to larger loss of higher order modes, increasing the system MDL by more than 15 dB at 6 µm coupling offset. This study highlights the necessity to build a strong understanding of the splice- and connector offset tolerances for future SDM fiber transmission systems.

## Experimental Setup

The experimental setup for the investigation of the coupling offset tolerance in a 15-mode fiber transmission system is shown in Fig. 1. To establish signal quality conditions as in a fully loaded wavelength-division multiplexed (WDM)/SDM transmission system, a full C- and L band WDM signal covering more 80 nm bandwidth between 1528 nm and 1608 nm was generated. This consisted of a sliding test-band, using three tunable laser sources and a dummy-band, generated from the laser lines of a single optical comb source. The WDM channel spacing was 25 GHz. The test-band was generated in two dual polarization IQ modulators (DP-IQ), driven by a four-channel arbitrary waveform generator (AWG), operating at 49 GS/s, generating 24.5 GBaud 16-QAM signals with a root-raised cosine pulse shaping with a roll-off factor or 0.01. The dummy channels were modulated in a single-

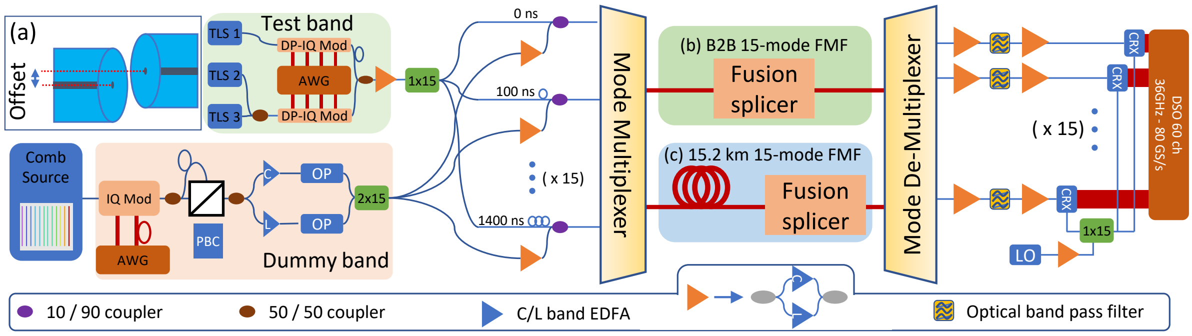


**Fig. 1:** Experimental setup for the investigation of the coupling offset tolerance in a 15-mode fiber transmission system. Inset (a) shows the offset at the coupling point between two FMFs, adjusted in the fusion splicer. Inset (b) shows the back-to-back (B2B) configuration and (c) includes 15.2 km transmission fiber.

polarization IQ modulator (SP-IQ), followed by optical processors (OPs) for spectral flattening and to carve a notch into the dummy channels to accommodate the test-band. In absence of 15 equal transmitter setups, spatially de-correlated copies of the signal were generated by splitting the test-band in a 1x15 coupler and delaying each of the 15 arms by multiples of 100 ns in delay fibers. Test- and dummy-channels were subsequently combined in 10 dB couplers after amplifying the dummy channels to 23 dBm total launch power. The 15 spatial channels were then multiplexed in a multi-path light conversion (MPLC)-based mode-multiplexer (MUX)[12]. The 15-mode FMF output signal from the MUX was then either directly connected to a similar de-multiplexer (DE-MUX) (inset (a)) or spliced to a 15.2 km 15-mode transmission fiber (inset (b)). The 15-mode fiber[13] had a graded-index core profile and a core diameter of 28.2 µm. The fiber had attenuation below 0.22 dB/km for the four lowest order mode-groups, with increase loss up to 0.34 dB/km in the highest order mode-group at high-L band wavelengths. The loss of the MUX and DE-MUX was approximately 9 dB each[6].

To investigate the impact of a lateral connector offset, either the output fiber of the MUX or the far end of the 15.2 km FMF were placed in a fusion splicer together with the FMF side of the DE-MUX, as indicated in inset (a) of Fig. 1. The fusion splicer was configured to reach a certain lateral offset between 0 µm and 6 µm with 0.1 µm precision. To avoid unequal cleave angles between measurements, the two fibers were not spliced but placed at 5 µm gap to each other. For signal reception, the 15 spatial channels from the DE-MUX were amplified before tunable bandpass filters selected a WDM channel under test. The signals were then mixed with local oscillators in coherent receivers, before the signals were digitized in a 60 channel real time oscilloscope, operating at 80 GS/s and with 36 GHz electrical bandwidth. Offline digital signal processing (DSP) consisted of a data-aided, time-domain, 30$\times$30 multiple-input / multiple-output (MIMO) equalizer using 281 half-symbol duration spaced equalizer taps, running in a loop with a phase-recovery algorithm. The signal quality was measured through the Q-Factor, estimated from direct error-counting of 10 µs long traces. We also extracted the singular values of the transmission channel for MDL estimation as detailed in[14].

## Results and discussion

We first analyze the impact of the coupling misalignment on the MDL of the transmission system. Figures 2(a) and (b) show the 30 squared singular values (without legend) of the 30$\times$30 transmis-

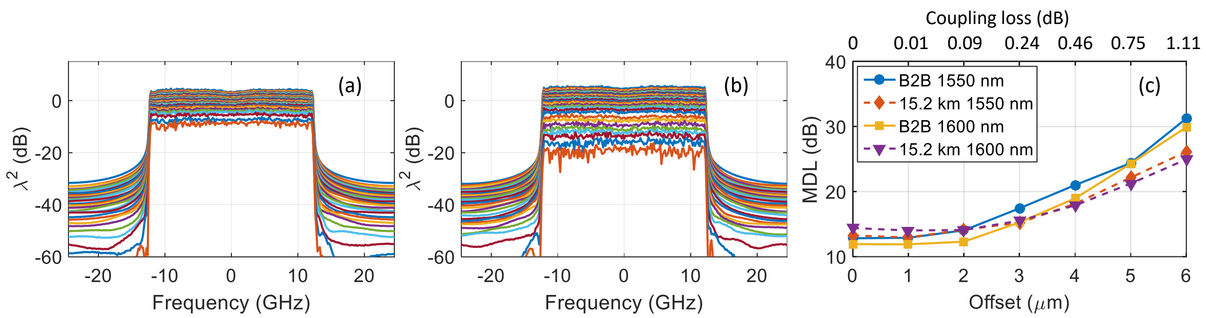


**Fig. 2:** (a) and (b) Squared singular values of the frequency-dependent transmission channel matrix in back-to-back (B2B) configuration with (a) 0 µm and (b) 6 µm offset. (c) MDL as a function of the lateral offset of the WDM channel at 1550 nm.

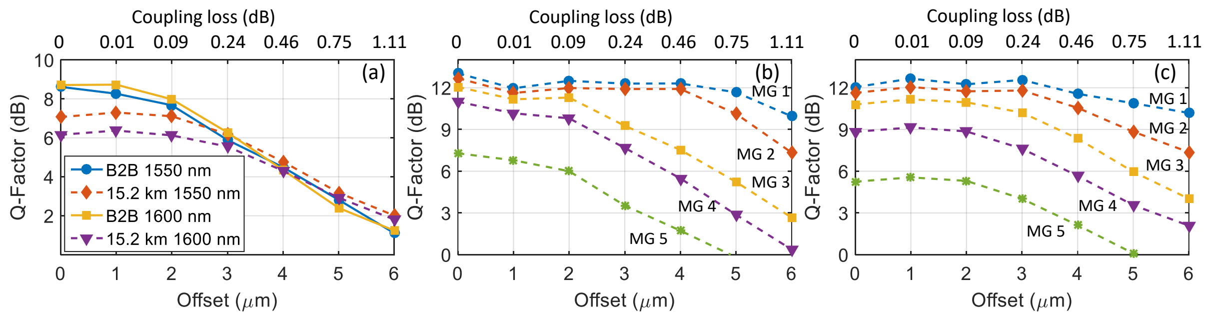


**Fig. 3:** Q-Factors as a function of the coupling offset (bottom axis) or coupling loss (top axis) for (a) two wavelength channels in back-to-back and after 15.2 km transmission. (b) and (c) mode-group (MG) resolved Q-Factors for the WDM channel at 1550 nm in (b) back-to-back and (c) after 15.2 km transmission

sion channel matrix[14] in B2B configuration. Figure 2 (a) shows the singular values without lateral offset and (b) with 6 µm offset. The transmission channel quality is generally higher if the singular values are similar, e.g., if the 30 lines are closer to each other. Hence, it is qualitatively visible from Figs. 2(a) and (b) that the lateral coupling offset reduces the channel quality. To quantify this, MDL is calculated as the the ratio of the largest to the smallest frequency-averaged squared singular values[14]. Figure 2(c) shows the system MDL as a function of the coupling offset on the bottom axis and the corresponding measured coupling loss on the top axis. While the MDL is larger after transmission compared to the B2B case for both wavelength channels, the MDL increase is smaller after 15.2 km transmission for the same offset, compared to the B2B measurement. This is presumably due to modal mixing during transmission that can be beneficial to reduce MDL. We note that the measured MDL is higher compared to reported values for a 6-mode and a 10-mode fiber at similar offsets[8], while this is not unexpected since the fiber in this experiment guides 15 modes.

Figure 3 shows the measured Q-Factors as a function of the coupling offset on the bottom axis and the coupling loss on the top axis. Figure 3(a) shows the Q-Factors, averaged over all fiber modes for two wavelength channels, in B2B configuration and after transmission. In B2B configuration, both wavelength channels have similar Q-Factor penalty when increasing the coupling offset. After transmission, the WDM channel at 1600 nm has a higher Q-Factor penalty in the absence of any coupling offset, as previously measured in the same fiber[6]. With increasing coupling offset, the Q-Factor penalty becomes similar for both WDM channels. Consistent with the MDL measurements of Fig. 2(c), the Q-Factor at 6 µm offset is higher after transmission compared to B2B. Figure 3(a) also shows that relatively small coupling losses, e.g., of 0.24 dB already lead to a significant performance penalty of more than 2 dB in the B2B case.

Figures 3(b) and (c) show the mode-group (MG) resolved Q-Factors for the WDM channel at 1550 nm in B2B (b) and after 15.2 km transmission (c). In both scenarios, the lower order mode-groups have a higher Q-Factor at low coupling offset but also suffer less from high coupling offsets. This is presumably due to the higher confinement of these mode-groups to the center of the fiber core. At high coupling offset, higher order mode-groups have a higher Q-Factor after transmission compared to the B2B scenario. We attribute this again to modal coupling during transmission that effectively spreads the signals over more modes and hence reduces the impact of the lumped MDL generation from the coupling offset.

## Conclusion

We have presented an experimental study of the performance penalty of a lateral coupling offset in a space-division multiplexed 15-mode fiber transmission system. The study has shown no significant offset tolerance difference between two wavelength channels, one at 1550 nm and one at 1600 nm. We have further demonstrated that lateral coupling offsets of up to 6 µm (corresponding to 1.1 dB lumped loss) can lead to a mode-dependent loss increase exceeding 15 dB. This translates into a Q-Factor penalty of more than 6 dB, considering 16-QAM modulated signals at 24.5 GBaud. The presented study highlights the importance of establishing a strong understanding of the entire hardware ecosystem for future SDM transmission systems, including splice and connector tolerances.

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