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Experimental Demonstration of Coherent Transmission over MMF and of the Impact of Connectors Offset

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ABSTRACT
We experimentally demonstrate the possibility of coherent transmission over multimode fiber and discuss its tolerance to offsets in connectors.
Keywords: Fiber optic communications, coherent detection, multimode fibers, offset launch.

1. INTRODUCTION

In intra-data center (IDC) interconnects, multimode fibers (MMF) are largely deployed for distances up to 300 m since they enable using VCSEL-based transceivers at 850 nm, which have significantly lower costs than all other short reach transceiver options. However, VCSEL+MMF transmission, even with newer OM4 and OM5 category fibers, have well-known maximum capacity limits due to multimodal dispersion, that make today transmission at more than 50 Gbit/s per wavelength over 300 m a difficult task.

In this paper, extending the work presented in [1-3], we experimentally investigate on the transmission of coherently detected PM-QPSK signal over MMF (CoH-MMF) links, showing potentially excellent performances when central launch is implemented, but also analyzing in detail the strong dependence on connector offsets. Our proposal can be of practical interest for IDC situations where a vast MMF installed base can be reused to upgrade the link capacity. Obviously, the cost saving due to MMF re-use is balanced by the significantly higher cost of coherent transceivers based on single mode fiber (SMF) (that is anyway constantly decreasing, as planned in the 400G ZR standardization initiative), but this techno-economic discussion is outside the scope of this paper.

The novelty of this paper compared to [1-3] is in the proposal of using standard coherent technologies but also in the detailed study of the power penalty that may be induced by practical offsets in the connectors that can be present along the link. In particular, we demonstrate CoH-MMF on 296 meters of OM3 MMF for 32 GBaud PM-QPSK, showing a very large available power budget (more than 33 dB) when center launch is enforced. Then we experimentally measure the impact of offsets in the SMF-MMF, MMF-MMF and MMF-SMF transitions, and confirm them by a numerical model based on [4], showing an excellent agreement between experiments and theory. Finally, using this model, we present a Monte-Carlo analysis of the resulting loss when several connectors are present along the link.

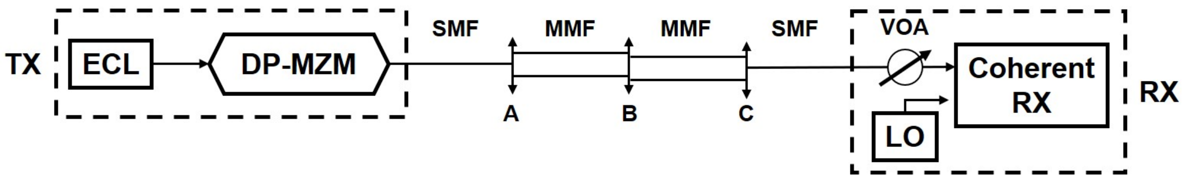

Figure 1. Experimental setup of the proposed CoH-MMF transmission system. ECL: External Cavity Laser; DP-MZM: Dual Polarization Mach Zhender Modulator; VOA: Variable Optical Attenuator; LO: Local Oscillator.

2. EXPERIMENTAL SETUP AND SENSITIVITY CURVES

The experimental block diagram of the proposed CoH-MMF system is depicted in Fig. 1. The transmitter includes an external cavity laser (ECL) and a dual-polarization Mach-Zehnder modulator (DP-MZM) driven by a 92 GS/s arbitrary waveform generator (AWG) to generate 32 GBaud PM-QPSK signals. The modulator output SMF fiber is directly coupled to the MMF link and, on the other end, the MMF link output is connected to the SMF fiber input of a commercial coherent receiver (CR). For obtaining baseline performances we used standard FC connectors, which in laboratory conditions we saw ensure a very good central launching condition. As we will show in the rest of the paper, the performance of this system is exceptionally good, due to the well-known fact that graded-index MMF (of OM3 and OM4 type) have a fundamental mode that couples very well to the SMF mode for central launching. Moreover, when this is achieved, the MMF has unexpectedly small coupling to higher order modes, even under significant bending, as shown in [6]. In fact, we verified experimentally that higher order mode excitation in the MMF in a practical situation would be much more likely generated by spurious lateral offsets in optical connectors along the links, therefore we focus our study on the investigation of the resulting system penalty.

To this end, we organized our experimental setup to be able to laterally offset the fiber in three possible positions, indicated in Fig. 1 as interface "A" (SMF-to-MMF), "B" (MMF-to-MMF) or "C" (MMF-to-SMF). To experimentally emulate lateral offset in connectors, we used a PI Hexapod®, an electro-mechanical nano-positioner that provides motion in six degrees of freedom (three axes and associated tilts) with sub-micron accuracy. In particular, we first automatically obtain a "perfect" central alignment (both laterally and in terms of angular tilt) for each of the three considered interfaces, then we move one fiber in an XY-plane transverse to the Z-direction of fiber propagation to precisely insert a lateral offset. Thanks to the sub-micrometer alignment capability of the used instrument, we manage to have an extremely narrow air gap between the two fibers (in the µm range).

We measured the system performance in terms of bit error rate (BER) as a function of the received optical power P_{RX}, varied at the CR input through a variable optical attenuator (VOA) after propagation over a 296-meter long OM3 fiber. Fig. 2a shows the sensitivity curves for different offset conditions at point A (SMF-to-MMF transition). There is no significant deviation from the back-to-back (B2B) sensitivity curve for offsets up to 4 µm on both X and Y axes parallel to the fibers facet, and the available power budget in this case was measured to be more than 33 dB (-6 dBm average transmitted power and sensitivity at BER=$3\cdot10^{-2}$ equal to -39.3 dB). Fig. 2b quantitatively shows how the penalty at BER=$3\cdot10^{-2}$ grows as the offset is increased in the XY plane. Given the observed circular symmetry (not shown) only positive offsets have been considered on both X and Y directions.

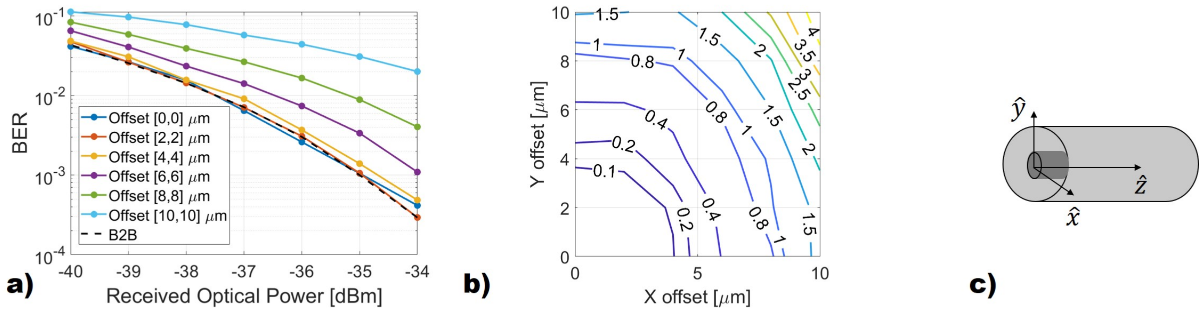

Figure 2. a) Sensitivity curves at different offset launch conditions at point A (SMF-to-MMF) and b) sensitivity penalty with respect to the zero offset condition at BER=$3\cdot10^{-2}$. c) Axes arrangement with respect to the fiber core center.

3. POWER LOSS IN SMF-MMF-SMF LINKS

In [4] Amphawan et al. derived an analytical formula to predict the power coupling coefficient of each mode for a SMF-to-MMF offset launch. They describe the total coupling coefficient as the overlap integral over the area of the fiber core of the product between the Gaussian field associated with the fundamental LP_{01} mode of a SMF and the field of all the modes of an MMF. Here we use that expression to build a numerical model that can emulate the configurations of Fig. 1 and return the offset-induced optical power loss at the junction between the two fibers. This model was then validated by experimental results shown in the following. Fig. 3 shows the additional loss in dB as a function of the offset, i.e. a loss normalized to the maximum found at the center of the core area ([X offset, Y offset] = [0,0]). The experimental loss for the SMF-MMF-SMF link without any lateral offset was measured to be 2.6 dB. Fig. 3a and 3b present respectively the experimental and simulation results when moving the nano-positioner at interface "A". As the modes coupling is reciprocal also for the "C" interface (MMF-to-SMF) only the set of results measured and simulated at point A is shown, but similar results were also observed at point C. The comparison highlights a remarkable match, especially in the central area for offsets up to 10 µm. For larger offsets, in the vicinity of the core-cladding separation, small discrepancies can be observed likely due to the infinitely parabolic refractive index profile approximation needed in [4] to derive an exact analytical expression for the mode coupling coefficients. Fig. 3c and 3d present the same results when offsetting at interface "B" (MMF-to-MMF). An even better match can be observed for offsets up to 15 µm. Fig. 3 confirms the validity of our model, at least in the most significant area of ±10 µm on both axes around the center. From a system point of view, we observe that the additional loss remains smaller than 2 dB for more than 5 µm lateral offset.

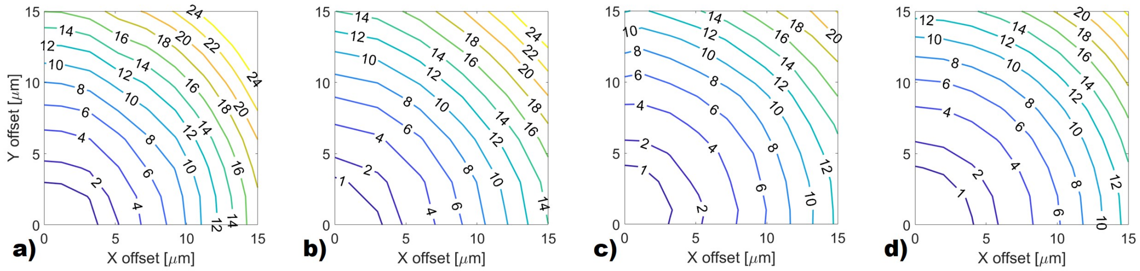

Figure 3. Optical power loss in dB as a function of the offset on both axes parallel to the fibers facet. a) Experiment and b) simulation at point A (SMF-to-MMF), c) experiment and d) simulation at point B (MMF-to-MMF).

In a realistic intra-DC environment, the signal can traverse several connectors. Using the theoretical model, we thus run Monte-Carlo simulations considering random offsets at the "A" and "C" interfaces, and then also at a variable number N_{MMF} of MMF-MMF connectors along the link. Offset distribution was modeled as Rayleigh distribution with mean μ_{off} in the range 2 μm ≤ μ_{off} ≤ 3 μm, as shown in [5]. We performed a 2000-iteration Monte Carlo simulation to obtain the cumulative distribution function (cdf) of the resulting power loss, which is presented in Fig. 4. Fig. 4a shows that when there is no MMF-to-MMF connections (N_{MMF} = 0) for μ_{off} = 2 μm the extra-loss is less than 5 dB in 100% of the cases. Considering the huge available power budget (33 dB, see Section 2), this can be easily tolerated. Fig. 4 shows that the extra loss quickly increases for increasing N_{MMF} and μ_{off}. For instance, for the extreme case of N_{MMF} = 6 and μ_{off} = 2 μm the extra-loss can reach 15 dB and less than 40% cases yield a loss smaller than 5 dB. The results shown in Fig. 4 can be used to statistically dimension the system, but also show that the proposed system can realistically tolerate at most N_{MMF} = 2 connectors for a typical μ_{off} = 2-2.5 μm, when the overall loss is below 10 dB with a probability extremely close to 100%.

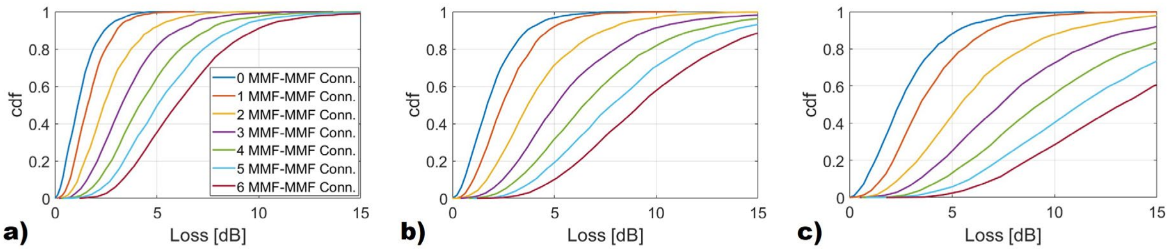

Figure 4. Cdf of the total optical power loss for several numbers of MMF-MMF connections. The offset on the two axes parallel to the fibers facet has a Rayleigh distribution with a) mean=2 μm, b) mean=2.5 μm, c) mean=3 μm. Legend in a) applies to b) and c) as well.

4. CONCLUSION

We have presented a detailed analysis of an MMF-based coherent transmission system for intra-DC scenarios when an offset launch introduced by commercial connectors is present at the interface between SMF and MMF fibers. Our experimental results show that for a 32 GBaud PM-QPSK transmission over 296 meters of OM3 MMF a really promising power budget of 33 dB is available and a 1 dB sensitivity penalty is obtained at 6 μm offset on both axes parallel to the fiber facet when the offset is applied either at point A or point C in the setup of Fig. 1. In addition to the sensitivity reduction an offset launch also introduces a power loss, that is a power budget penalty. Experiments show a 2 dB loss for a [4 μm, 4 μm] offset. An analytical model taken from [4] for the calculation of the power loss at the interface between any combination of SMF and MMF fibers has been validated through experiments, with remarkable accuracy especially in a 10 μm-by-10 μm area around the core center. Through this model we have also shown that the cascade of several MMF-to-MMF connections can severely degrade the performance of a CoH-MMF system. In the best-case scenario of a Rayleigh offset distribution with mean μ_{off}=2 μm 100% of the 2000 Monte-Carlo iterations yielded a power loss lower than 5 dB with no MMF-to-MMF connections on the optical path, whereas for six MMF-to-MMF connectors only about 30% iterations resulted in power loss below 5 dB. In the worst-case with μ_{off}=3 μm these percentages drop to 90% and less than 10% respectively. Moreover, three and one MMF-to-MMF junctions can be tolerated in the best (μ_{off}=2 μm) and worst (μ_{off}=3 μm) case respectively, considering a 10 dB power loss acceptable, given the exceptional available power budget.

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