# Stable Coherent MIMO Transport over Few Mode Fiber Enabled by an Adiabatic Mode Splitter

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**Abstract** *Simulations confirm stable MIMO transport of three channels over a two mode fiber - even in the presence of fiber bending induced mode coupling - enabled by a new adiabatic mode splitter output coupler.*

## Introduction

In the last years, the expected steady growth of the data traffic fosters the investigation of means to further boost the capacity of an optical fiber. Recently the exploitation of the space domain has been re-formulated, which was so far not in the focus for ultra-high bit-rate transmission, i.e. the transport of different data channels over different modes of a multi-mode fiber (MMF)[1,2]. If mode conversion cannot be excluded the application of so called multiple-input multiple-output (MIMO) digital signal processing (DSP) concepts at receiver side has already been proposed about a decade ago[3-6] for recovery of the original data channels. Even though feasibility was demonstrated using direct detection receiver (DD)[5,9], the strong statistically spread of the maximum capacity[6,10] due to drifting propagation conditions of a MMF can only be eliminated (1) by a move to coherent optical receivers[4] and (2) by harmonizing the MMF mode number and the transmitter/receiver number[10].

In this paper we numerically investigate the stability of coherent MIMO transmission over a few mode fiber (FMF) for the simplest case of a two mode fiber. The main sources of instability are included in the assessment, i.e. mode coupling at the interface between transmitter / receiver single-mode fiber (SMF) pigtails and the FMF and microbending induced coupling along the FMF link. Moreover, a passive optical waveguide structure - an adiabatic mode splitter - is proposed as output coupler solution which strongly improves the stability.

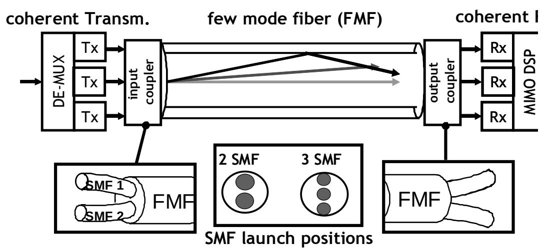


**Fig. 1:** Coherent MIMO transmission system over a few mode fiber (FMF). Bottom insets: butt coupling of Tx and Rx SMF pigtails w. FMF and SMF launch position for 2 or 3 pigtails

## MIMO transmission system and fiber model

In Fig. 1 the coherent MIMO transmission system is sketched out. The input data are distributed among coherent transmitters (modulators fed by the same laser source) which are then coupled into a FMF. Since we will study of the impact of mode mixing on the stability only, we assume FMF's differential modal delay (DMD) negligible compared to the symbol period, which might be the case for OFDM transmission and allows to describe the transfer function between a transmitter j and receiver i by a simple complex number $h_{ij}$.

As shown by the lower right inset, the SMF pigtails are butt coupled into the FMF. The core diameter of the FMF step index fiber and the SMF were 24µm and 5µm, respectively. For butt coupling 2 or 3 SMFs were positioned in the core area of the FMF, as illustrated for 2 SMFs by the insets in Fig.1. The core index of the FMF was adjusted to a value that two LP (linear polarized) modes were supported, namely $LP_{01}$ and $LP_{11}$. $LP_{11}$ exists in two degenerated forms with mode fields having 0° and 90° azimuthal rotation. The coupling factors k between 2 or 3 SMFs and three 3 LP modes were calculated by the use of normalized field distribution $E_{LPi}$ and $E_{SMFj}$, respectively: $k_{LPi,SMFj} = \iint E_{LPi} E^{*}_{SMFj} dA$.

Analogously, at the receiver side output coupling factors $k_{SMFi,LPi}$ quantifying the amplitude transfer between LP mode j and receiver pigtail i were calculated too.

The inclusion of microbending is crucial to assess the stability of MIMO transport since it will be a dominating source of mode mixing in systems bridging lengths of many kilometers. Bending induced coupling is described by the coupled mode equation (CME)

$dA_i / dz = -j\beta_i A_i + \Sigma(jc_{ik} A_k)$. The coupling coefficients $c_{ik}$ quantify the power exchange per length unit between two initially orthogonal modes i and k and deviates from 0 in the case of fiber bends[11]. In the simulation model we approached the distributed coupling between all three modes by three sections of constant coupling between pairs of two LP modes. The three analytical solutions were written as three complex 3x3 matrices $B_i$ connecting the vector of LP mode amplitudes at bend input with the amplitude vector at the output. As an example: in case of the two degenerated $LP_{11}$ modes with identical phase constants $\beta_i$, i.e. $\beta_2 = \beta_3$. the solution can describe a rotation of the $LP_{11}$ fields. The phases $\varphi_i$ of the three LP modes were summarized in a diagonal matrix B = [exp(j$\varphi_1$),..,exp(j$\varphi_3$)]

## Capacity simulation

The capacity, i.e. the theoretically maximum achievable bit-rate, per Hertz bandwidth for a given signal-to-noise ration $\rho$ can be calculated by $C = \log_2 \left\{ \det \left( I_M + \rho H \left( H^* \right)^T \right) \right\}$ if the complex channel transfer matrix H between the different transmitter and receiver SMFs is known[4,6,10]; (I=identity matrix). The MxN transfer matrix H for N SMF input pigtails and M output pigtails was formed by the product H = $K_{OUT}PB_3B_2B_1K_{IN}$. $K_{IN}$ and $K_{OUT}$ are coupling matrices collecting $k_{LPi,SMFj}$ and $k_{SMFi,LPi}$, resp. The microbending in $B_i$ and the mode phases in P were varied statistically to emulate drifting fiber conditions which lead to statistically changing transmission quality capacity.

In the case of input and output butt coupling, stable transmission is not possible, as illustrated by the spread of the three leftmost overlapping capacity histograms in Fig. 4 obtained from 1000 statistical samples of P and B calculated for transmitter - receiver counts of 2-2, 2-3, and 3-3. For the 3-3 case the spread amounts to 48% (from 0.17 to 0.24 bit/s/Hz). Compared to the maximum possible value of 3 bit/s/Hz ($\rho$=1) the lower values are due to butt coupling loss.

## Adiabatic mode splitter (AMS)

Guided by the idea that an ideal mode splitter could eliminate mode mixing at input and output and reduce C spreading by stable transformation of each LP mode to a different SMF output port, we proposed an adiabatic mode splitter (AMS) which is a passive waveguide structure with a waveguide layout shown in Fig. 2. We assume that it can potentially be realized as fused fiber coupler[12] formed by different fiber types or as crystal fiber structure[13]. The operation of the AMS is based on the robust mode splitting property within a few millimeter length of directional couplers constructed by different waveguides[14]. The key element of the AMS is an index taper (see Fig. 2 and leftmost part of Fig. 3) which is formed by an increasing core index for waveguide 1 and 2 along propagation axis z. At z = 0 the four waveguides are identical and three local normal modes (LNM)[15] exhibit mode field distribution similar to the three LP modes of the FMF. Hence low loss butt coupling between FMF and AMS should be possible. By gradually increasing the core index elevation $\Delta$n of waveguide pair 1 and 2 from 0.001 to 0.002, the different LP modes propagating through the AMS concentrate in different waveguide pairs. This is confirmed by the three remaining graphs in Fig. 3 showing waveguide power vs. z for mode launching at z = 0 of $LP_{01}$, $LP_{11}$90° and $LP_{11}$0°, resp. Each curve, labelled by the waveguide number, was calculated by numerically solving a CME[15] for the four coupled waveguides. The FMF modes concentrate in waveguide pairs 1,2 or 3,4, resp., with an isolation of at least 13 dB (rightmost plot in Fig. 3). In a consecutive section of the AMS, the separation taper shown in Fig. 2, the extinction

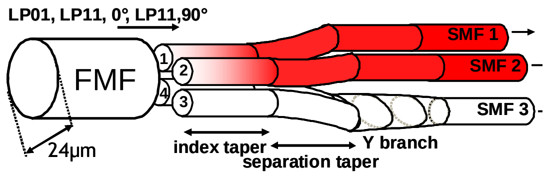


**Fig. 2:** Index profile of adiabatic mode splitter (AMS) transforming FMF's LP modes to modes of SMF pigtails. Core index color indicates gradual core index change: $\Delta$n= 0.001...0.002.

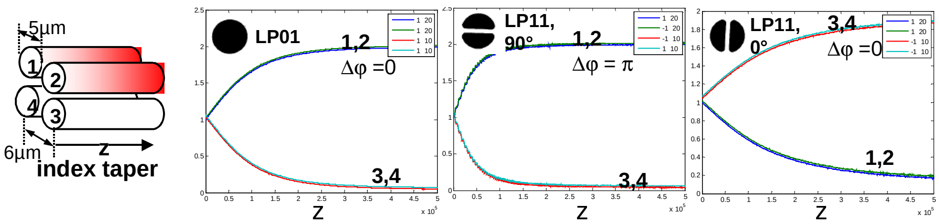


**Fig. 3:** Power evolution vs. z for waveguides 1 to 4 of index taper (left) for $LP_{01}$, $LP_{11}$,0° and LP $_{11}$,90° modes (from left to right). Curves are labeled by waveguide No. and signal phase difference $\Delta\varphi$ of waveguide pair.

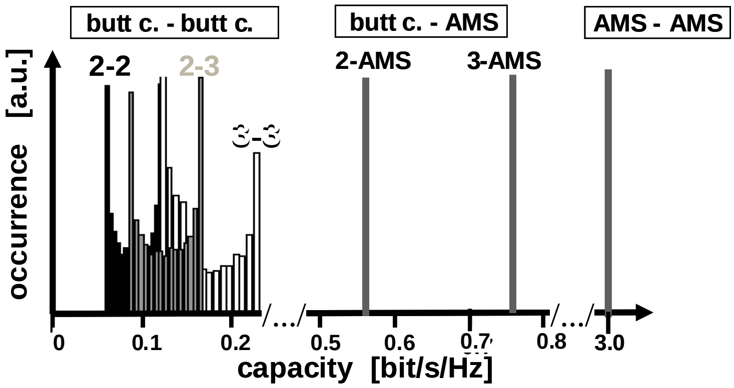


**Fig. 4:** Capacity histograms for MIMO with a 2 mode FMF for different input / output couplers:
Left histograms: Butt coupling at input and output: 2-2, 2-3, and 3-3 SMF pigtails
Middle bins: Butt coupling of 2 and 3 SMFs at input, AMS coupler at output
Right bin: AMS couplers at input and output.

ratio is further increased by a gradual increase of the distance between the waveguides from 6µm to 30µm. In a third section (Y branch) waveguides 3 and 4 are merged to SMF3 since they solely carry the $LP_{11}0°$ signal. Even though $LP_{01}$ and $LP_{11}90°$ are not transformed to different output ports but evenly split among SMF1 and SMF2, the splitting distinguishes in phase differences $\Delta\varphi$ of 0 and $\pi$, resp. The transfer matrix of the ideal lossless AMS with infinite extinction ratio is

$$K_{AMS} = 1/\sqrt{2} \cdot \begin{pmatrix} 1 & 0 & 1 \\ 1 & 0 & -1 \\ 0 & \sqrt{2} & 0 \end{pmatrix}.$$

It links the LP mode amplitude vector $(A_{LP01}, A_{LP11,0°}, A_{LP11,90°})^T$ with the AMS output amplitude vector $(A_{SMF1}, A_{SMF2}, A_{SMF3})^T$.

A replacement of the output butt coupled fibers by the AMS leads to the middle cluster of isolated histogram bins in Fig. 4, showing that the spreading of C is eliminated by the AMS with three attached receivers. Moreover, the zero loss increases the calculated capacity value. Attaching the ideal AMS also at the input of the FMF leads the histogram bin at the theoretical maximum value of 3 bit/s/Hz.

## Conclusions

Capacity statistics was numerically analyzed for coherent MIMO transmission over few mode fiber (FMF) supporting two modes only ($LP_{01}$, $LP_{11}$). Drifting modal phase and coupling due to microbending was taken into account. Beside butt coupling between SMF pigtails and FMF to connect coherent transmitter and receiver to the FMF, also a new optical waveguide structure forming an adiabatic mode splitter (AMS) was proposed.

This splitter is based on adiabatic mode separation in a waveguide structure with gradually changing refractive index profile and waveguide separation. Even though it does not completely separate the LP modes, its output signals allow a further lossless demultiplexing of the transmitted channels by MIMO processing in the DSP.

A strong variation of the capacity between 100% and 48% for butt coupling, mainly induced by mode coupling due to bending can completely be eliminated by applying the AMS at FMF output. Since the $LP_{11}$ exists in two degenerated forms with 90 degree rotated mode fields, the mode splitter needs to separate not only two but three modes. On the other hand, this allows for the transport up to three channels over the two mode fiber.

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