Mode Coupling Analysis in Optical MIMO Systems

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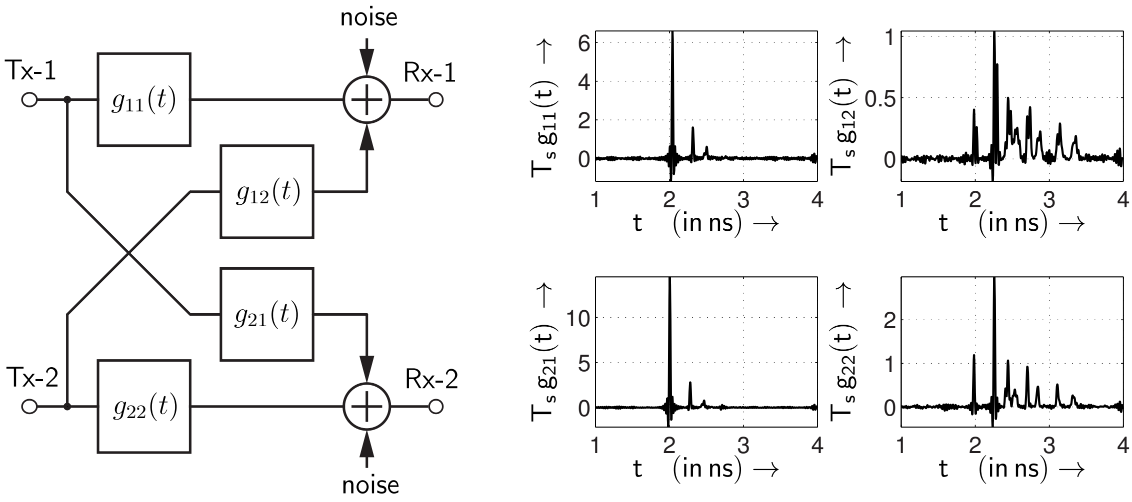
Abstract

Optical multiple-input multiple-output (MIMO) systems have attracted a lot of attention in the fiber-optic community. The concept of optical MIMO is well-elaborated. However, the investigation of optical MIMO systems requires adequate simulation models. In this work an approach based on mode transfer matrices is presented. The obtained simulation results are confirmed by measurements carried out in a testbed transmitting through 1 km OM4 fiber at an operating wavelength of 1327 nm.

1 Introduction

Spatial multiplexing in fiber-optic systems is based on transmitting data streams on different modes or mode groups at the same time as well as in the same frequency band. It can be realized with single-mode fiber (SMF) to multi-mode fiber (MMF) splices choosing different radial offsets for mode-selective excitation, and multi-mode fusion couplers are used for mode multiplexing and demultiplexing [4]. For this setup the measured multiple-input multiple-output (MIMO) impulse responses $g_{\nu\mu}(t)$ and the corresponding MIMO channel model are depicted in Fig. 1 when transmitting through a 1.4 km MMF channel [3]. Here, the variables $\nu = 1, \dots, n_\mathrm{R}$ and $\mu = 1, \dots, n_\mathrm{T}$ denote the MIMO output and input indices, respectively. Figure 2 illustrates the SMF to MMF alignment with the radial offset δ.

Launching centric from the SMF into the MMF, i.e. $\delta = 0\,\mu\mathrm{m}$, mainly excites low order modes, confer to the impulse responses with $\mu = 1$ (Tx-1). In contrast, using an eccentricity of $\delta = 15\,\mu\mathrm{m}$ excites higher order modes, see responses with $\mu = 2$ (Tx-2). Compared to standard SMF transmission, modal dispersion needs to be taken into account. Since an operating wavelength of 1327 nm is used, the chromatic dispersion is negligibly small. These measured results are taken as reference for modeling the optical MIMO channel.



(a) MIMO channel (b) Measured MIMO impulse responses

Figure 1: (2×2) MIMO channel and measured impulse responses with respect to the pulse frequency $f_{\mathrm{T}} = 1/T_{\mathrm{s}} = 620\,\mathrm{MHz}$ at 1327 nm operating wavelength

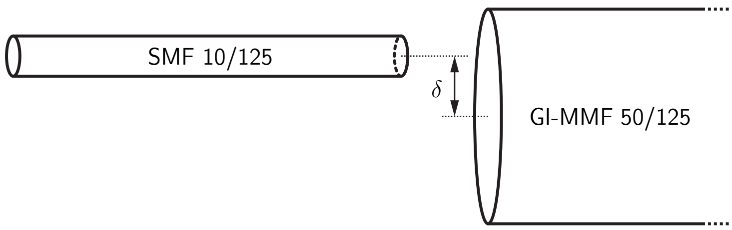


Figure 2: Fiber core alignment of a SMF to MMF splice with a certain offset δ for mode-selective excitation

2 Time-domain Simulation of Optical MIMO Channels

The profound understanding of optical MIMO requires adequate simulation models. In this work a time domain approach based on mode transfer matrices (MTMs) is presented [2]. For the model validation, a testbed configuration as shown in Fig. 3 is analyzed. In

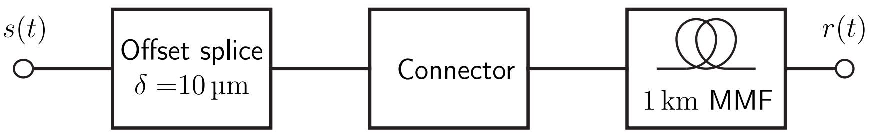


Figure 3: Testbed configuration for model validation

each system block of Fig. 3, mode coupling is considered by introducing MTMs [1]. The power exchange between the LP_{01} mode of the SMF and the N modes supported by the MMF can be defined by the mode transfer vector

$$\boldsymbol{c} = \begin{pmatrix} c_1 & c_2 & \ldots & c_n & \ldots & c_N \end{pmatrix}^{\mathrm{T}} \qquad \boldsymbol{c} \in \mathbb{R}^{(N \times 1)}, \tag{1}$$

where the number of modes $N = V^2/4$ depends on the normalized frequency V. With this notation c_1 describes the power coupling to the LP_{01} mode of the MMF and e.g. c_3

Power coupling coefficient	c_1	c_2	c_3	c_4	c_5	c_6	...
MMF mode	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}	...

Table 1: Mapping of the power coupling coefficients to their corresponding mode

is the coupling factor to the LP_{21} mode as highlighted in Tab. 1. The power of the N supported modes by the MMF can be obtained by

$$\boldsymbol{p}_{\text{out}} = \boldsymbol{c} \cdot P_{\text{in}}^{(1)} , \tag{2}$$

with the vector $\boldsymbol{p}_{\text{out}}$ being defined as follows

$$\boldsymbol{p}_{\text{out}} = \begin{pmatrix} P_{\text{out}}^{(1)} & P_{\text{out}}^{(2)} & \dots & P_{\text{out}}^{(n)} & \dots & P_{\text{out}}^{(N)} \end{pmatrix}^{\text{T}} \qquad \boldsymbol{p}_{\text{out}} \in \mathbb{R}^{(N\times 1)} . \tag{3}$$

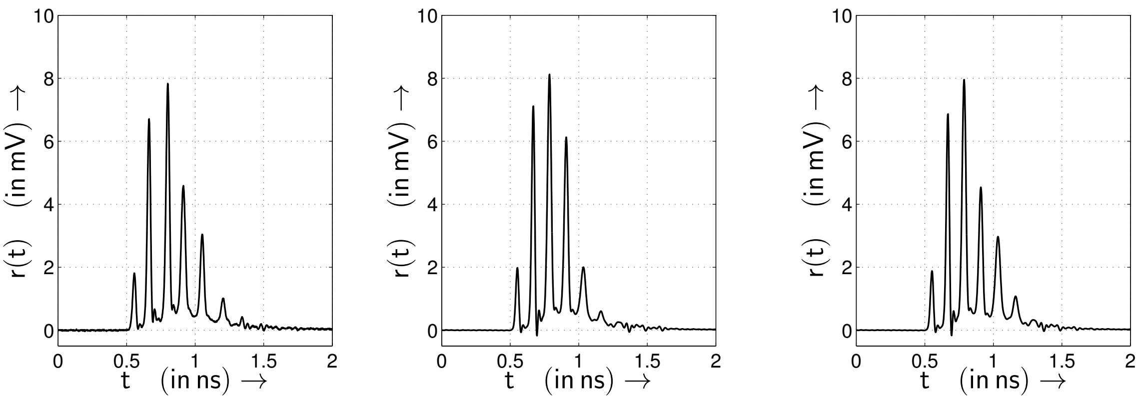
The parameter $P_{\text{in}}^{(1)}$ describes the power of the incident LP_{01} mode in the SMF, whereas $P_{\text{out}}^{(n)}$ is the power of the n-th outgoing mode in the MMF. Taking all power coupling coefficients c_n into account, the corresponding impulse response is given by

$$g_{\text{m}}(t) = \sum_{n=1}^{N} c_n \cdot P_{\text{in}}^{(1)} \cdot \delta(t - \tau^{(n)}) \ . \tag{4}$$

Here, the parameter $\tau^{(n)}$ denotes the mode dependent propagation time in the OM4 fiber. Referring to [1], power coupling between principal mode groups in this fiber is not considered. In addition to modal dispersion, described in (4), the effect of chromatic dispersion is taken into account by the impulse response $g_{\text{c}}(t)$ resulting in the overall impulse response

$$g(t) = g_{\text{c}}(t) * g_{\text{m}}(t) \ . \tag{5}$$

Considering our testbed configuration shown in Fig. 3, mode coupling is only occurring in the offset splice and the connector.



(a) Measurement (b) Sim. with ideal connector (c) Sim. with real connector

Figure 4: Comparison of measurement and simulation results

3 Simulation Results

For verification of the simulation results, measurements are carried out taking a 1 km OM4 fiber and transmitting at a wavelength of 1327 nm. The comparison between the measurement and the simulation is shown in Fig. 4. The results show that the simulation is congruent to the measurement when considering the power coupling coefficients of the underlying testbed, by introducing a MTM for a real connector.

4 Conclusion

In this paper an optical MIMO component has been described, focussing on mode transfer matrices. Based on this description a simulation has been carried out in order to obtain the corresponding impulse responses. The simulation results have been confirmed by testbed measurements. Future work could extend this description to other components of an optical MIMO system.

References

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