Modeling and Design Framework for SDM Transmission Systems

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ABSTRACT
We present a sophisticated simulation framework for few-mode fiber based space division multiplexing (SDM) transmission systems supporting the characterization of the interplay between linear and nonlinear fiber effects, and design of key components such as optical amplifiers. We demonstrate its capabilities by discussing applications related to doped and un-doped multimode fiber design, linear and Kerr-induced mode coupling, and effective means for digital equalization at the receiver side.
Keywords: SDM, few-mode fiber, multimode fiber, transmission system, differential mode gain, simulation.

1. INTRODUCTION

The ultimate capacity of single-mode-fiber (SMF) has been shown to be limited by fiber nonlinearities [1]. One promising approach to further increase the capacity of fiber-based transmission systems is Space Division Multiplexing (SDM) [2]. SDM can be realized using for instance fiber ribbons, multicore (MC) fibers or few-mode fibers (FMF). SDM systems impose additional challenges for the system designer: beyond transmitter and receiver design, compensation of attenuation, noise, chromatic dispersion and nonlinearity, it is necessary to properly take into account inter-modal interactions, most importantly linear mode coupling [3] and Kerr-induced cross-phase modulation (XPM) [4].

To design SDM systems efficiently, it is very beneficial being able to rely on flexible and accurate simulation tools for multimode-based transmission technologies. These tools should provide not only accurate models of individual components, but also allow integration of these components to analyze and optimize their impact on system performance. Beside SDM systems, another important design task represents the development of high-bandwidth short-range solutions (e.g. for data center connections). This task requires the optimization of simpler systems, based on cheaper multimode fibers and On-Off Keying (OOK) transmitters based on vertical-cavity surface-emitting lasers (VCSELs).

In this paper, we describe our work towards a unified simulation framework addressing the aforementioned challenges. We start in Section 2 with an outline of the multimode signal model and other important elements of the simulation framework. In Section 3, we discuss the modeling of signal propagation in SDM systems taking into account linear and nonlinear coupling in multimode fiber and digital equalization at the receiver. In Section 4, we describe multimode Erbium-doped fiber amplifier (EDFA) modeling, approaches to determine the amplifier impact on system design and means for optimizing the amplifier design.

2. MULTIMODE SIGNAL MODEL

One of the key capabilities of a powerful simulation environment for optical transmission systems is a common format to exchange information between models of individual components (building blocks). This enables the flexible combination of individual building blocks supporting variable implementations of system models. Building blocks can either be different modules (functions) within the same software, or of distinct software products communicating with each other using pre-defined interfaces.

The most important interface part between blocks represents the optical signal model. For single-mode applications (including two polarization modes), the signal model [5] contains complex envelopes of the electromagnetic field in Jones vector representation. For memory efficiency (especially in case of wide frequency range), the model supports multiple frequency bands (MFB), where the signal contains several discretized complex envelopes on non-overlapping spectral bands.

For multimode applications, we extended this signal model to support multiple spectrally-overlapped complex envelopes accompanied with information of their spatial profiles and other properties (such as indices of individual modes, propagation constants). Note that this additional information describes mostly not the signal itself (the information being transmitted), but the spatial and spectral distribution of the refractive index in the corresponding fiber. Typically, transmission systems utilize just one type of fiber for the whole link, and the information of the mode profile is the same for all blocks it passes.

For flexible representations of the multimode signal, we implemented a signal model, which separates out the calculation and storage of the mode information (including their spatial profiles) in dedicated building blocks (mode solvers). As a special variant, these blocks also offer datasheet (or ‘measured’) operation: when the actual information of refractive index profile is not available or has been pre-calculated by other means, information about effective indices, group velocities (or differential mode delays) and similar characteristics can be specified directly allowing to optimize other parameters of the SDM system.

This approach enables to refer to the necessary fiber structure (fiber type) in all building blocks that require it. Moreover, the signal model is less error-prone when optimizing the fiber structure: there is only a single point specifying the fiber type. On the implementation side [6], this model represents a generalization of the MFB approach with a mode label attached to each signal block and spectral overlap of individual signal blocks being enabled. In a similar way we apply the statistical representation of signals, as used to model broadband optical noise or signals without modulation details. Moreover, our approach can be further generalized to model multi-core fibers (MCF) supporting one (dual-polarized) or several modes in each core, or being described by several supermodes distributed over all cores.

3. SIGNAL TRANSMISSION IN MULTIMODE-BASED SDM SYSTEM

3.1 Simulation setup

In this section, we briefly discuss an application demonstrating our approach outlined above. We investigate an exemplary SDM system (Fig. 1) based on transmission over FMF supporting four LP modes (LP01, LP11, LP21, LP02). Since two modes are degenerated, a total of 6 dual-polarization channels are supported by this fiber. Each channel carries a 25 Gbaud dual-polarization quadrature phase shift keying (DP-QPSK) modulated signal and is coupled into a dedicated fiber mode using a mode coupler. This coupler model can emulate the behavior of a realistic device such as a photonic lantern. At the receiver side the output of each mode is detected using a coherent polarization-diversity receiver.

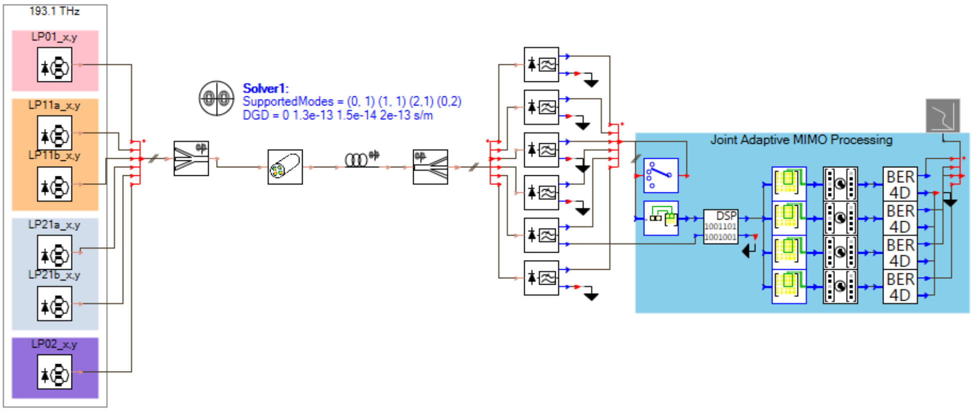

Figure 1. Simulation setup of 6 Channel SDM transmission system with MIMO equalization.

While converting several input single-mode signals, the multiplexer model (see Fig. 2, left), a special block not only simulates a mode coupler (idealized or taking into account cross-talks), but creates all structures necessary for multimode signal representation. Alternatively, a beam-to-fiber coupling model can be used to simulate the generation of a multimode signal in non-SDM links.

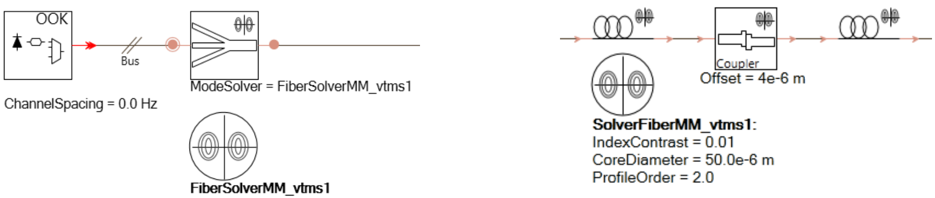

Figure 2. Combining single-mode outputs of several transmitters into one multimode signal (left) and simulation of splice-induced mode coupling (right).

3.2 Multimode fiber

The multimode fiber model takes into account linear effects such as dispersion (intra and inter-modal group velocity dispersion, chromatic dispersion, polarization mode dispersion (PMD)), and linear mode coupling, as well as the nonlinear Kerr effect. We assume a perfectly cylindrically symmetric fiber. In addition, the fiber modes are approximated as linearly polarized LP-modes, based on the approximation of weakly-guided fibers [7]. The propagation constants calculated by the mode solver for an ideal circularly symmetric fiber can be adjusted appropriately in order to account for fiber imperfections such as PMD or broken circular symmetry.

In real fibers, modes with similar propagation constant values couple strongly due to random perturbations of the waveguide geometry [3, 8]. Note that since SDM systems use digital equalization algorithms to reconstruct the signal at the receiver side mode coupling can be beneficial in a sense that it reduces the width of the impulse response, which in turn reduces the requirement on the receiver [3].

In absence of mode coupling the accumulated group delay difference between different modes scales linearly with distance, whereas in presence of modal coupling intermodal dispersion scales as the square root of fiber length [8]. Mode coupling due to random perturbations is a distributed process, but it can be modeled by dividing the fiber in unperturbed sections and applying random coupling at discrete points between these sections [3]. In such model the standard deviation of the accumulated inter-modal dispersion between different groups of coupled modes scales linearly with the number of fiber sections. In contrast, within each group of coupled modes the accumulated dispersion scales with the square root of section numbers. Lumped coupling due to splices can be modeled between different fiber sections using a dedicated building block as illustrated in Fig. 2, right.

The way the nonlinear Kerr effect manifests itself in optical fibers depends on the strength of linear mode coupling. If strong linear mode coupling occurs on a length scale much shorter than the length scale of nonlinear interactions then the nonlinearity can be averaged among all coupled modes. For each group of strongly coupled modes, this leads to a single Manakov equation with an averaged nonlinear coefficient [4]. Additionally, the Manakov equations are extended to a system coupled through nonlinear terms accounting for the Kerr coupling among different mode groups [9]. The values of the averaged nonlinear coefficients depend on overlap integrals involving the spatial mode profiles of the modes which are strongly coupled [9].

3.3 MIMO equalization

As the modes travelling at different velocity in multimode fiber couple during propagation [10], the outputs of all modes must be processed jointly using a multiple-input multiple-output (MIMO) filter [11]. Equalization is achieved in the frequency domain and taps optimization is performed using the least mean square (LMS) algorithm. In the present example the maximum differential group delay is 0.2 ps/m between LP01 and LP02.

Under ideal conditions, mode-coupling takes place within mode-groups, or in other words between modes with similar velocity. However, mechanical stress (such as micro-bending) and splices can lead to mode-group coupling. As the size and complexity of the MIMO filter directly depends on the channel response, it is highly desirable to avoid inter-mode group coupling in FMF-based systems. The performance of the LP0x, LP11ax, LP21ax and LP02x channels are reported after 100 and 1000 km for varying number of MIMO taps assuming strong coupling condition in Fig. 3. The OSNR is the same in both cases (25 dB). Non-ideal taps adaption explains the difference between 100 and 1000 km for large number of taps.

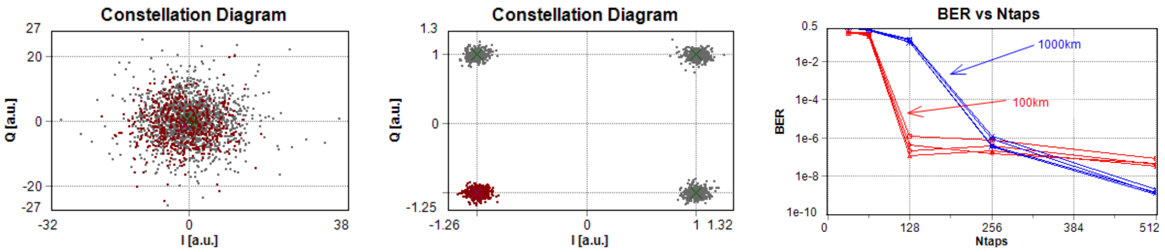

Figure 3. Exemplary constellation diagrams of uncompensated (left) and MIMO DSP-compensated (center) received signal. Plot of bit-error ratio (BER) vs. number of taps in MIMO filter for compensated receiver (right).

4. MM-EDFA MODEL

For successful elaboration and deployment of SDM networks an important factor will be the availability of optical amplifiers capable to simultaneously amplify different spatial channels [12]. Currently, fiber amplifiers represent a mature technology for single-mode transmission. Their design has been optimized to provide high signal bandwidth, low gain ripple, low noise level and high power efficiency. Flat gain spectrum allows avoiding deviation of WDM channel powers from the optimum, and thus ensuring a proper balance between the impact of noise and fiber nonlinearities. For SDM applications gain equalization should be achieved not only in the spectral domain, but also for spatially separated channels [13]. As the latter show different intensity distributions minimizing the Differential Modal Gain (DMG) becomes a challenge for the amplifier design.

To tackle this problem we report here a model for multimode Er-doped fibers that represents an enhanced version of [14] and is implemented within our simulation framework [6]. The mode solver block calculates the LP fiber modes for signal and pump waves. Spatial beating between different LP modes and between the vector modes constituting the LP modes are neglected, which seems to be a reasonable approximation for spectrally-broadened modulated signals [15]. Hence, the total light intensity is given by the sum of spatial intensity distributions of all fiber modes. The concentration of excited Er ions is governed by the local light intensity and the radially-dependent doping profile. Both of them are resolved in transversal dimensions. For solving the propagation problem the modal gain coefficients are calculated by numerical integration of the transversal overlap between the modal intensity and the excited ions distributions. Design factors that control the DMG include the refractive index profile, doping distribution and pump power distribution among the fiber modes. All of these factors affect the aforementioned transversal overlap.

For a given amplifier configuration mode-dependent gain, noise figure, DMG and other EDFA characteristics are calculated in a single simulation run. Thus, the doped fiber model allows analysis and optimization of the amplifier design (see Fig. 4). The model supports both, sampled multimode signals and signals in statistical representation. For this reason the amplifier output can be directly re-launched into the next fiber span in the SDM system simulation.

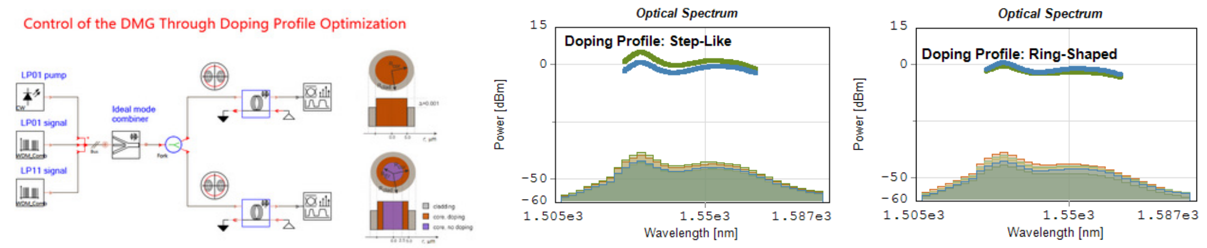

Figure 4. Simulation setup characterizing a multimode EDFA (left) and output spectra of LP01 and LP11 modes for a step-like (center) and ring-shaped (right) doping profile. The ring-shaped profile provides a larger overlap with the intensity distribution of the LP11 mode leading to a smaller DMG.

5. CONCLUSIONS

Summarizing, we have presented a powerful simulation framework for optical signal transmission in multimode fiber systems. We illustrated its key functionalities on the basis of specific examples: SDM transmission link with MIMO equalization and optimization of DMG in multimode EDFA. Our proposed signal model supports a new level of abstraction (separation of transversal structure definition from signal propagation), and thus provides additional flexibility necessary to overcome the difficulties arising from the need for accurate modeling and optimization of multimode (and multicore) components and systems.

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