Simulation and Verification of a Multicore Fiber System

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ABSTRACT

In this paper, a simulation model of a multicore fiber in the linear regime is presented. We describe how to digitally represent the fiber and introduce a modelling scheme based on Coupled-Mode theory and Power-Coupled theory to analyze the system performance of multicore fibers. In order to validate the investigated model, the obtained simulation results are compared to our own measurements of a 7-core multicore fiber transmission link and to results from previously published experiments.

Keywords: space division multiplexing, multicore fiber modelling, multicore erbium-ytterbium fiber amplifier.

1. INTRODUCTION

In sciences, simulation models allow the comprehensive study and testing of prototypes and systems before being built or implemented, in order to analyze, and characterize them thoroughly [1]. In optical communications, fiber models permit to understand perturbations in the optical fiber, and to investigate mitigating strategies among other things. We propose a linear wave-plate simulation model of a multicore fiber (MCF) based on theoretical coupling theories to estimate crosstalk (XT) between cores and verify it by means of an experimental integrated multicore system [2]. The structure of this paper is as follows. Section 2 introduces the structure of the simulation model along with the physical analysis of the fiber characteristics and XT estimation methods. Then, the model is validated in section 3 against real experiments. Finally, section 4 draws the conclusions.

2. MULTICORE FIBER MODELLING

Figure 1 shows the adopted linear MCF. The fiber is segmented in wave-plates and disturbances are locally computed for each given fiber piece. The considered impairments for every core are: attenuation (α), differential group delay (β_1), chromatic dispersion (β_2), higher-order dispersion (β_3), polarization-mode dispersion (P), and linear inter-core XT (C_{nm}).

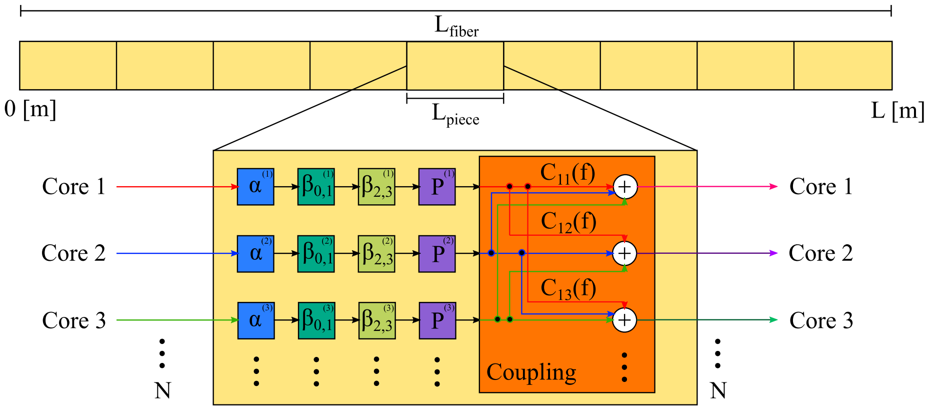

Figure 1. Fiber structure for a simulation model of an MCF.

Estimating the coupling matrix **C**, which describes the individual crosstalk contributions among *N* cores, is the main problem to solve. Out approach consists of two steps: we first estimate C by using the Finite Element Method (FEM) to solve electromagnetic equations on a cross-section of MCF, and then use coupling theories to calculate crosstalk along the length of the MCF.

2.1 Estimation of propagation constants

To analyze an optical waveguide, we start with the Helmholtz wave equation for an isotropic homogeneous medium in scalar form:

$$\nabla^2\varphi + \beta^2\varphi = 0 \tag{1}$$

where β^2 represents the eigenvalue of the equation and ϕ, the electric or magnetic field. In physical terms, β^2 would be the propagation constant of one mode traveling in the fiber, since the scalar wave equation is used in Electromagnetics to analyze the propagation of plane waves (electrical and magnetic modes) in waveguides [3].

Equation (1) is solved minimizing the following functional:

$$F(\varphi)=\frac{1}{2}\iint_S\left[\left(\frac{\partial\varphi}{\partial x}\right)^2+\left(\frac{\partial\varphi}{\partial y}\right)^2+\beta^2\varphi^2\right]ds \quad (2)$$

where S refers to the cross-sectional area of the waveguide to be observed. For a given MCF structure, FEM yields the propagation constants for the various cores.

2.2 Coupled-Mode Theory

From calculated the propagation constants, it is possible to obtain the cores' effective refractive indices, which are necessary to compute the mode-coupling coefficients (MCC), i.e. the physical values that express how efficiently power is transmitted between cores [4]. A simplified expression to calculate the MCCs for homogeneous trench-assisted fibers based on its physical and geometrical characteristics is presented in [5]. We use this expression, since the MCF in our experiments fulfills the requirements for this formula.

Coupled Mode Theory (CMT) models the way two or mode waveguides interact with each other over a certain distance depending on the propagation constants of the individual waveguides and the MCCs. The differential equations that describe such a phenomenon are called coupled mode equations (CME):

$$\frac{dA_n}{dz}=-i\cdot\sum_{n\neq m}\kappa_{nm}A_m\exp\left(i\left(\beta_n-\beta_m\right)z\right) \quad (3)$$

where A_m represents the complex signal of core m, and β is the equivalent propagation constant of a given core. To take into account twisting and bending effects, and random structural inhomogeneities of the fiber, we apply random phase offsets in each fiber segment. The complex values that solve the CME form the coupling matrix **C**.

2.3 Power-Coupled Theory

Power-Coupled Theory (PCT) models the power interaction between two or mode optical waveguides [4]. Similarly to CMT, PCT defines a set of differential equations to calculate the power transfer relation between cores:

$$\frac{dP_n}{dz}=\sum_{n\neq m}h_{nm}\left(P_m-P_n\right) \quad (4)$$

where h_{nm}, and P refer to the power coupled coefficient that relates two cores [6], and the total power in a given waveguide, respectively. Due to its nature, the output of the differential equation does not contemplate phase shifts within the fiber segment; it just gives a power relation between a given core and the amount of XT that it experiences; however, when considering standard single-input single-output digital signal processing, this modelling method is sufficient, since from the receiver perspective the whole inter-core XT behaves like additional noise.

3. Simulation and experimental results

3.1 FEM calculation and validation

Table 1 shows the characteristics of the 7-core MCF that we have used for the experiments and Fig. 2 shows the mesh used in our FEM calculations and the corresponding simulated normalized power distribution.

Table 1. 7-core MCF parameters.

Parameter	Value
Core radius	5.11 µm
Core-to-trench radius	10.5µm
Trench width	5.1 µm
Core-cladding index difference	0.3%
Cladding-trench index difference	-0.7%
Pitch distance	49.3 µm
Cladding diameter	195 µm

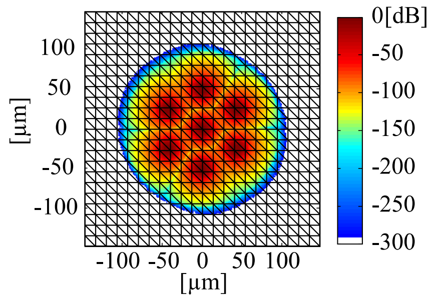

Figure 2. Cross-sectional view of the normalized power distribution in a 7-core MCF.

Propagation constants for all cores of the MCF were calculated using FEM according to 2.1 and crosstalk was derived from the power transfer equation (4) using PCT. Four MCF designs from the literature [7]-[10], and our own 7-core MCF were evaluated to verify the crosstalk estimation from simulations. In Fig. 3, the filled markers denote simulation results using 44,402 triangular elements (298 elements per each spatial axis), which deviate by less than 3 dB from the reported crosstalk values in the literature (empty markers). In particular, the 7-core MCF used in our experiments [2] has a measured worst-case XT of -58 dB, whereas the simulation predicts a value of -56.75 dB; demonstrating the validity of using FEM as a way to model an MCF and its characteristics.

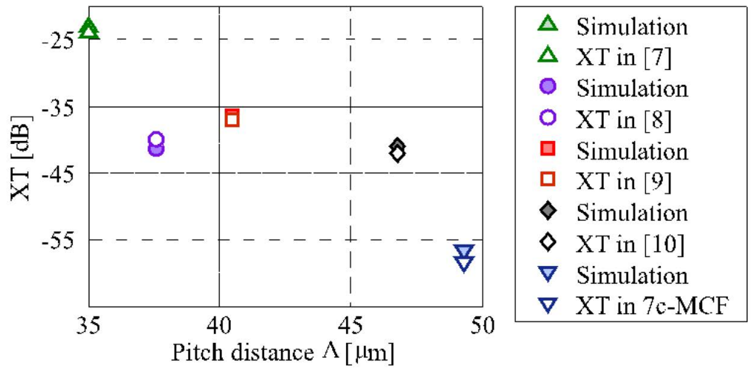

Figure 3. Comparison between measured XT in manufactured MCFs in the literature and XT estimations from MCF modelling from FEM and PCT.

3.2 Simulation and experimental setup

Figure 4 shows the experimental setup used for multicore experiments and that has been modeled in our simulation program. A test channel is generated at 1561.4 nm and combined with 14 neighboring 100 Gbit/s QPSK channels between 1558 nm and 1564 nm in a 50 GHz grid. The test channel is modulated using QPSK, 8QAM, and 16QAM to produce channels with bit rates of 100 Gbit/s, 150 Gbit/s, and 200 Gbit/s, respectively. The combined signal is split into two: a copy is fed directly to the core-under-test (CUT), whereas the second copy of the signal is further split to produce 6 copies for the remaining cores of the MCF. The 6 copies for the neighboring cores are de-correlated by means of delay lines of various lengths. The signal for the CUT is the only one put through a recirculating loop; the rest are just acting as interfering signals. The total power of the signal at the input of the recirculating loop is 4 dBm, corresponding to a power per channel of -7.76 dBm. The signal goes through a low-speed polarization scrambler (PS) before going into the integrated multicore link [1] consisting of fan-in/fan-out couplers, integrated cladding-pumped multicore erbium-ytterbium-doped fiber amplifiers (MC-EYDFAs), and a 60-km homogeneous trench-assisted multicore fiber. Afterwards a gain-flattening filter (GFF) is introduced to flatten the spectrum. After the loop, a single core erbium-doped fiber amplifier (SC-EDFA) boosts the signal before an optical bandpass filter (OBPF) selects the test channel. The optical signal is translated into the electrical domain by a coherent receiver and detected by a real-time oscilloscope and standard digital signal processing is performed: resampling to 2 samples per symbol, chromatic dispersion compensation in the frequency domain, carrier frequency offset and channel estimation, and clock and timing recovery. For the transmission experiments, we assume soft-decision forward error correction (FEC) with 20% overhead.

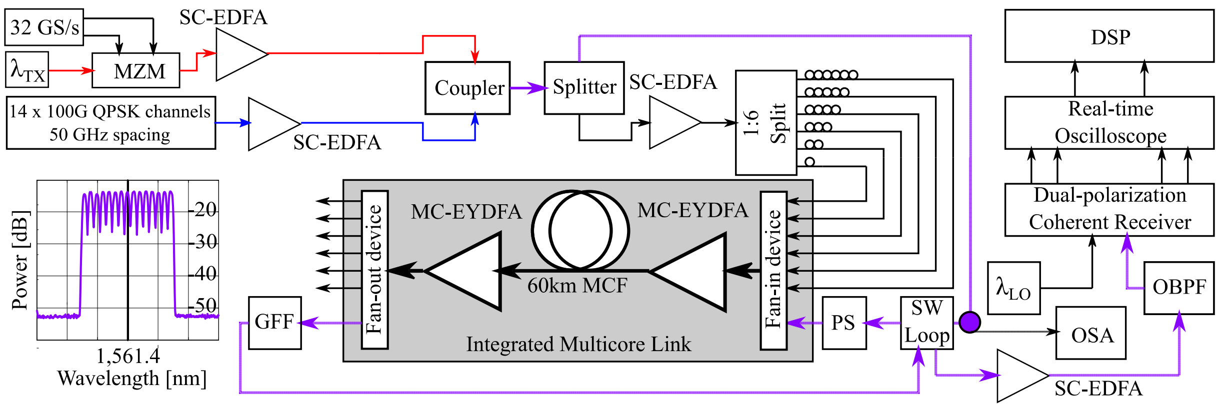

Figure 4. Experimental setup of a 7-core MCF system with an integrated multicore link.

3.3 BER vs. Distance

Figure 5 shows the BER as a function of the distance for various modulation formats and cores, i.e. the center core (CC) and one outer core (OC). The bigger markers, corresponding to PCT and CMT, display a similar trend to the lines showing the experimental results (EXP), falling within a reasonable margin. Therefore we conclude that the proposed simulation model reflects accurately the overall performance of the experimental MCF system for both coupling theories.

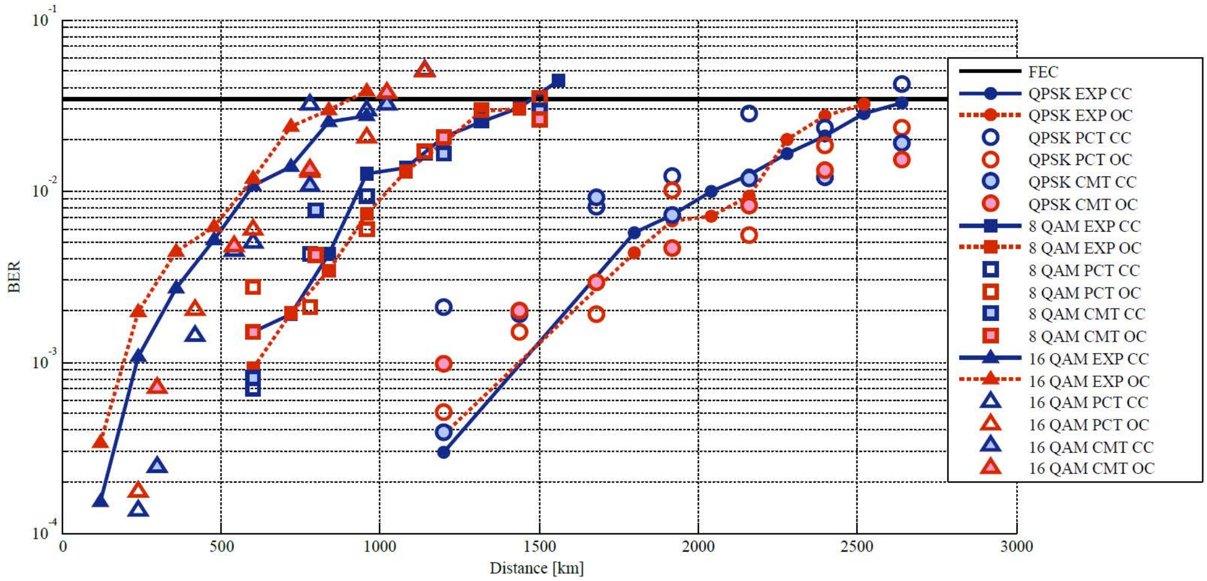

Figure 5. Comparison between experimental transmission results and simulation results from CMT and PCT.

4. CONCLUSIONS

We have implemented a multicore fiber model based on Finite Element Method, and Coupled-Mode Theory and Power-Coupled Theory to analyze arbitrary MCF fiber systems, and compared its simulation results to experimental data from a 7-core MFC system. Simulation and experimental results from the literature are no more than 3 dB apart concerning crosstalk estimation, whereas results from WDM transmission simulations show close agreement with the experimental results.

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