Nonlinear Impairment Scaling in Multi Mode Fibers for Mode Division Multiplexing

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Abstract: The scaling of nonlinear effects in multi mode transmission fibers with mode count has been investigated. Results indicate that transmission reaches comparable to standard single mode fibers are achievable for at least 100 modes.

1. Introduction

The data transport capacity of single mode fiber (SMF) based transmission systems is limited due to noise and nonlinear effects, potentially resulting in a capacity crunch [1]. Space division multiplexing has been proposed as an approach to further increase fiber capacity [2]. This can be realized by increasing the number of cores, the number of modes per core or a combination of both. A fiber with a single core which enables the propagation of multiple modes (MMF) provides the highest mode density and therefore potentially the highest capacity for a given cladding diameter – in addition to a potential for the realization of more energy efficient amplifiers [3] and less complex components [4]. However, the modes share the same fiber cross section area. The high spatial density also potentially results in strong interactions between the modes while they propagate in the transmission fiber due to nonlinear signal interactions. In the linear case and without mode dependent losses, a fiber with M spatial modes provides M times the capacity of a single mode fiber. We have addressed the question, whether this capacity increase still holds, if nonlinear effects are taken into account.

Starting from a single mode fiber, there are two options to increase the number of guided modes – either by increasing the core radius or by increasing the numerical aperture (NA), i. e. the refractive index difference between the core and the cladding glass. In order to avoid issues with losses due to stronger Rayleigh scattering and stresses due to differing thermal expansion coefficients of involved glasses, the numerical aperture should not be increased by more than a factor of three compared to the value NA = 0.1 known from standard single mode fibers (SSMF). Hence, mode counts of 100 or above require a significant increase of the core radius. The required increase of the core radius has an important impact on the scaling of the strength of nonlinear effects with the number of modes, which is depicted in Fig. 1.

The diagram shows a sketch of the impact of mode count on effects determining the strength of nonlinear impairments. As mentioned above, a higher number of modes guided by the core goes along with a larger core radius. The growing core area increases the effective mode field areas (A_{eff}). As the relevant nonlinear effects such as the Kerr effect depend on spatial power density, increasing A_{eff} reduces the strength of nonlinear impairments, as depicted by the blue line. Intra channel nonlinear effects such as self-phase modulation in MMF are weaker than in SSMF as the A_{eff} of the fundamental mode is larger and the mode field areas of higher order modes tend to be even larger than the one of the fundamental mode.

However, the increasing number of modes contributes more potential nonlinear interaction partners. This increases the strength of nonlinear impairments resulting from inter channel nonlinear effects such as cross-phase modulation (XPM) and four wave mixing (FWM). The growing contributions of inter channel nonlinear effects to nonlinear impairments due to increasing mode count are depicted by the red line. However, increasing A_{eff} also reduces the strength of inter channel nonlinear effects. An interesting question is, whether the weakening impact of the increasing A_{eff} or the strengthening impact of the growing number of interaction partners dominates in the overall dependence of nonlinear impairments on mode count in practical fiber designs. We intend to provide some contributions to an answer to this question.

Several attempts have been made to characterize the scaling of nonlinear impairments with mode count. They can be divided into analytical approaches and numerical simulations.

2. Analytical approaches

Many analytical approaches are based on the observation that the Kerr effect can lead to signal degradations with similar properties as the ones caused by the effect of amplified spontaneous emission (ASE) [5,6]. Consequently, nonlinear impairments are modeled as a source of noise. As the probability distribution function (PDF) of this noise contribution is usually assumed to be Gaussian, the analytical approaches are frequently referred to as Gaussian noise models. These models have been applied successfully to estimate the impact of nonlinear effects in single mode fiber based transmission. In order to extend their applicability to multi mode fibers, the nonlinear Schrödinger equation (NLSE) or the Manakov equation can be generalized to multi mode propagation.

One major advantage of such analytical models is their ability to enable deriving general rules about the strength of the interaction of various mode combinations by inspection of the relevant equations [5]. Self-phase modulation (SPM) and cross-phase modulation (XPM) can be interpreted as degenerate four wave mixing (FWM) processes. Consequently, strong nonlinear impairments will only occur, if strong four wave mixing components are generated. Strong four wave mixing requires good phase matching of propagating components. This observation leads to important consequences for the scaling of nonlinear impairments with the number of modes. The total number of mode combinations that can result in the generation of four wave mixing components grows with the third power of the number of modes guided by the fiber core, i. e. M^3. Out of these components, only $2M$ will have non negligible strength due to sufficiently good phase matching.

In addition to phase matching, the strength of nonlinear impairments depends on the overlap between mode field distributions, which can also be interpreted as the inverse of the effective area for given mode combinations. As shown in Fig. 2, which contains the intra and inter modal nonlinear coefficients for 15 LP modes guided by a sample graded index core fiber, the efficiency of nonlinear interactions as determined by the overlap is generally higher for the intra modal case than for the inter modal one. However, inter modal efficiencies are in the same order of magnitude and cannot be neglected due to the large number of combinations.

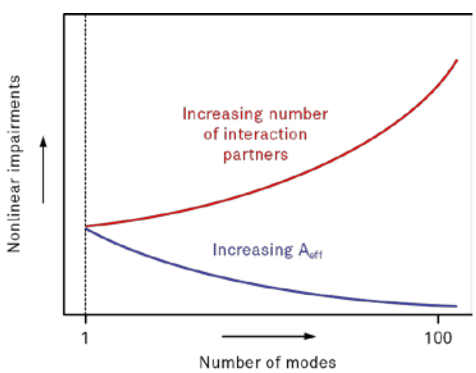

Fig. 1. Contributions to the scaling of the strength of nonlinear impairments with the number of modes

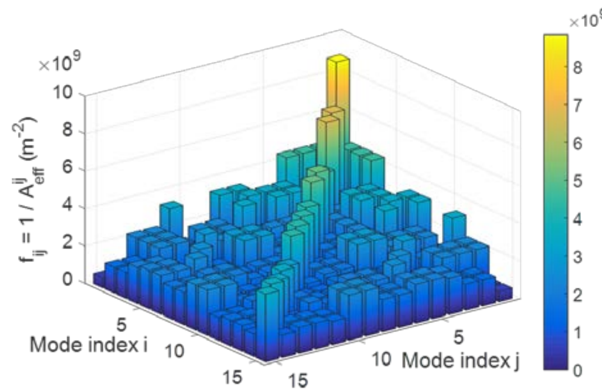

Fig. 2. Nonlinear interaction strengths of different mode combinations determined by mode field overlaps

The analytical model based on Gaussian noise calculation has been used to study a high capacity transmission link [7]. Wavelength division multiplexing (WDM) combs with constant spectral density and a total width of 4 THz are assumed to propagate in 55 modes of a multi-mode fiber with parabolic index profile. According to the calculated OSNR values, the fundamental mode in the multi mode fiber suffers from similar nonlinear impairments as the same mode in a standard single mode fiber, if all modes are used for transmission. Higher order modes feature larger mode field areas and therefore suffer from smaller nonlinear penalties. As a consequence, the overall system capacity exceeds the capacity of 55 single mode fiber based systems with the same configuration.

3. Numerical simulations

Analytical models enable a decent estimation of the strength of nonlinear impairments, but they require several simplifying assumptions. Moreover, they are not very well suited to study the performance of transmission characteristics in detail. In the single mode case, numerical simulations based on split step Fourier methods are widely deployed to consider many more details of transmitter, receiver, and fiber characteristics and to validate the accuracy of the predictions from analytical models. We have developed such numerical simulation tools to study the signal propagation in multi mode fibers.

Major challenges for the deployment of numerical simulations arise from processing effort and memory requirements. Parallel processing on GPUs helps to achieve acceptable durations of simulations [8], but processing on multiple GPUs can be required due to limited available memory per GPU [9]. The developed numerical simulation tools have enabled us to study the evolution of signal quality degradation due to nonlinear effects, e. g. if the number of modes is increased by scaling up the core radius [10]. Results shown in Fig. 3 reveal that transmission with many modes can suffer from less nonlinear impairments than transmission in SSMF and that penalties decrease with increasing mode count, in accordance with the trends reported by the analytical estimations [7].

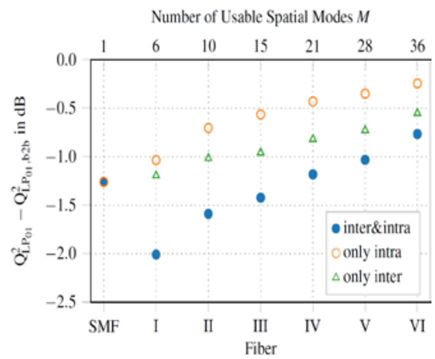

Fig. 3. Penalties from nonlinear impairments in multi mode fibers with rescaled core radius

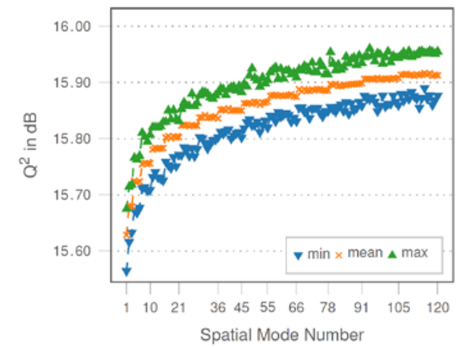

Fig. 4. Signal quality after transmission of 120 modes with 60 WDM channels over 400 km

The observed trends have encouraged us to increase the mode count beyond 100. Fig. 4 shows numerical simulation results for a transmission of 60 WDM channels in each of the 120 modes of a fiber with a core diameter of 62.5 µm over 400km, corresponding to a total number of 7,200 DP-QPSK signals with a symbol rate of 32 GBaud. As the Q^2 penalty due to nonlinear effects of the worst case mode, the fundamental mode, compared to the back to back case was only 0.35 dB, it is in the same range as in a single mode fiber based transmission system with a similar configuration. Propagation of even higher mode counts with similar penalties seems to be feasible.

4. Summary and conclusions

We have used analytical approaches and numerical simulations to investigate the scaling of nonlinear impairments in mode-division multiplexed multi mode fiber transmission, when increasing the number of fiber modes. Results indicate that signal degradations in a fiber with more than 100 modes can be less severe than in a standard single mode fiber for the same system configuration.

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