

Long-haul few mode fiber optic link with differential mode delay compensation on line amplifiers

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Abstract. This paper present results of simulation of the few mode fiber optic link with the differential mode delay compensation. There were considered some variants of compensation of differential mode delay and chromatic dispersion. The one of variants is the compensation at the far end of fiber optic link. And other is compensation at line amplifiers with two schemes of differential mode delay compensation.

1. Introduction

On the one hand, the telecommunication networks are development in the conditions of continuous growth in demand for increasing the network capacity [1]. On the other hand, the “nonlinear Shannon limit” limits the capacity of the today telecommunication networks based on usual single-mode optical fibers [2-4]. This stimulate researches of space division multiplexing with few-mode optical fibers that along with multi-core optical fibers are considered as an alternative to usual single-mode fibers. The few-mode optical fibers have already been developed [5-7]. The mode division multiplexers and few-mode amplifiers are developed too [4, 8-11]. There are examples of experimental demonstration of the capabilities of mode division multiplexing technologies using few-mode fibers for long-haul communication links [12-16]. The technologies of mode division multiplexing is of significant interest for future communication networks, but its practical application requires solving a number of problems. In particular, solutions to the problem of the influence on the quality of information transmission by individual modes of joint action of factors of differential mode delay and mode coupling. This factors along with chromatic dispersion, polarization mode dispersion and nonlinearity, limit the carrying capacity and length of the regeneration sections of fiber-optic links.

Some aspects of the functioning of long-haul few-mode fiber optic links were investigated by the simulation methods [17-25]. In particular, in [25], for two-mode fiber-optic transmission links, the possibility was shown a significant improvement for compared to traditional compensation of chromatic dispersion on the far end of the link by the chromatic dispersion compensating on linear optical amplifiers.

In the present paper, we were evaluated for such fiber optic links an advisability the differential modal delay (DMD) compensation on linear optical amplifiers (LOAs). There were simulated the two-mode fiber-optic transmission links with DMD compensation on LOA for the two cases. The one case is chromatic dispersion compensation on the far end of the fiber optic link. The other case is chromatic dispersion compensation on the LOAs together with DMD. The two schemes of DMD compensation were considered. The simulation data of fiber optic links with DMD compensation were compared

with the simulation data for the fiber optic links without DMD compensation. The results of the comparison are presented in this paper.

2. Model of the long-haul two-mode fiber optic communication line

Since the purpose of the work was to determine the feasibility of DMD compensating on LOAs, it was suggested that for this, as in [19, 21-25], it suffices to analyse in the two-mode fiber optic link the propagation of the LP01 and LP11 modes. In the general case, six modes propagate in such a line. There are the two orthogonally polarized modes for LP01 mode, the two orthogonally polarized modes for LP11a mode and the two orthogonally polarized modes for LP11b mode. As is known, the delay between orthogonally polarized modes is negligible compared to the delay between modes LP01 and LP11. The delay between modes LP11a and LP11b is also negligible compared to the delay between modes LP01 and LP11. This allowed us to consider as degenerate as orthogonally polarized modes, as well as modes LP11a and LP11b, and restrict ourselves to the analysis of the propagation of two modes LP01 and LP11.

To simulate the fiber optic links under investigation, the algorithm described in detail in [25] has been used. The process of signal propagation in a few-mode optical fiber taking into account the linear and nonlinear coupling of modes, can be represented as a system of nonlinear Schrödinger equations [26, 27]

$$\begin{aligned} \frac{\partial A_p}{\partial z} = & i(\beta_{0p} - \beta_{0r})A_p - \left(\beta_{1p} - \frac{1}{v_{gr}} \right) \frac{\partial A_p}{\partial t} - i \frac{\beta_{2p}}{2} \frac{\partial^2 A_k}{\partial t^2} + \\ & + i \sum_{lmn} f_{lmnp} \frac{\gamma}{3} \left[(A_l^T A_m) A_n^* + 2(A_l^H A_m) A_n \right] + i \sum_m q_{mp} A_m, \end{aligned} \quad (1)$$

where A_p - envelope of optical signal in p -th mode in time domain; β_{0p} , β_{0r} , β_{0p} - propagation constant, first derivation of propagation constant and group velocity dispersion for p -th mode, respectively; β_{0r} , v_{gr} - mean values of propagation constant and group velocity for p -th mode; γ - nonlinear coefficient; q_{mp} - linear mode coupling coefficient; f_{lmnp} - nonlinear coupling coefficient.

Linear mode coupling coefficient is defined by mode field overlap integral and refractive index perturbation internal and external factors. Nonlinear coupling coefficient is defined by mode fields overlap integral.

This equation can be simplified for particular cases of weak and strong mode coupling. In particular, for the weak mode coupling averaging random variations of the birefringence, the Manakov equation was obtained, differing by the coefficients 8/9 and 4/3 for the terms taking into account the self phase modulation (SPM) and the cross phase modulation (XPM) of the spatial modes, respectively [20]. For the strong mode coupling, when the strength of linear mode coupling is comparable with the coupling of linearly polarized modes, the coefficient of the nonlinear summand in the Manakov equation is determined in summary form over all modes, taking into account the overlap factor of the mode fields [20].

In general form, (1) can describe all regimes of propagation in few-mode fibers. To solve (1), the split-step Fourier method (SSFM) method and its various modifications has been widely used [20, 26].

In this paper, we propose to use the following approach: dispersion effects and linear coupling of modes are taken into account independently from nonlinear effects and nonlinear mode coupling.

$$\frac{\partial \mathbf{A}}{\partial z} = (\hat{C} + \hat{N}) \mathbf{A}, \quad (2)$$

where \hat{C} - is the operator takes into account attenuation, dispersion effects and linear mode coupling; \hat{N} - is the operator takes into account nonlinear effects and nonlinear mode coupling.

Neglecting nonlinear operator the system of coupled equations for optical signal Fourier transform can be represented as

$$\frac{\partial \tilde{\mathbf{A}}}{\partial z} = \hat{C} \tilde{\mathbf{A}}, \quad (3)$$

where $\tilde{\mathbf{A}}$ - is the column matrix $N \times 1$, formed from Fourier transform of optical signal in spatial modes; $\hat{\mathbf{C}}$ is the square matrix $N \times N$ taking into account dispersion effects and linear mode coupling.

Matrix coefficients $\hat{\mathbf{C}}$ are defined by:

$$C_{pp} = -\frac{\alpha}{2} + i\Delta\beta_{0p} - i\omega\Delta\beta_{1p} + i\omega^2 \frac{\beta_{2p}}{2}, \quad (4)$$

$$C_{mp} = C_{pm}^*, \quad (5)$$

where α - the attenuation coefficient;

$$\Delta\beta_{0p} = \beta_{0p} - \beta_{0r}, \quad \Delta\beta_{1p} = \beta_{1p} - 1/v_{gr}.$$

It should be noted that in this case it is assumed that the polarization modes are degenerate. To analyze the influence of mode coupling on the system performance the two mode regime was analyzed. The solution of system (3) for two modes can be found in the form

$$\begin{aligned} \tilde{A}_1(z) &= \exp(Bz) \left\{ \left[\cos(i\theta z) + i \frac{\sin(i\theta z)}{2\theta} (C_{22} - C_{11}) \right] \tilde{A}_1(0) - i \frac{C_{12}}{\theta} \sin(i\theta z) \tilde{A}_2(0) \right\} \\ \tilde{A}_2(z) &= \exp(Bz) \left\{ \left[\cos(i\theta z) + i \frac{\sin(i\theta z)}{2\theta} (C_{22} - C_{11}) \right] \tilde{A}_2(0) - i \frac{C_{21}}{\theta} \sin(i\theta z) \tilde{A}_1(0) \right\} \end{aligned}$$

where

$$B = \frac{C_{11} + C_{22}}{2} = -\frac{\alpha}{2} + i\omega^2 \frac{\beta_2}{2}$$

and

$$\theta = \sqrt{\left(\frac{C_{11} - C_{22}}{2} \right)^2 + C_{12}C_{21}}$$

Or

$$\theta = \sqrt{\left(\frac{\omega\Delta\beta_1}{2} \right)^2 + |q_{pm}|^2}$$

The equal group velocity dispersion $\Delta\beta_1 = \beta_{12} - \beta_{11}$ was assumed for propagated modes. This obtained equation is similar to solution in [28].

Analyzing presented above equations, one can conclude that there are periodical power exchange between propagated modes with spatial step and coupling strength determined by the parameter θ and q_{pm} . Because of the significant values of $\Delta\beta_1$, spatial step is of the order of millimeters, depending on the optical fiber construction, which leads to the necessity to use the average coupling factor.

At simulation, it is proposed to use the modified symmetric SSFM method written in general form as

$$A(z + \Delta z, t) \approx \exp\left(\frac{\Delta z}{2} \hat{D}\right) \hat{Q}(z) \exp(\Delta z \hat{N}) \exp\left(\frac{\Delta z}{2} \hat{D}\right) A(z, t)$$

where operator \hat{D} take into account attenuation and dispersion effects; operator \hat{Q} take into distributed and discrete mode coupling; operator \hat{N} take into account nonlinear effects; Δz is the step size.

The step size is determined by the strength of the dispersion and nonlinear effects or by the pulse walk-off in optical channels and should be smaller than the correlation length determining the mode coupling strength $\Delta z \ll 0.37/h$, where h is the linear coupling coefficient, 1/km.

At simulation the distribution of coupling coefficients formed by a random Gaussian process with a specified correlation function corresponding to the propagating regime. The discrete mode coupling taking into account using a unitary coupling matrix in the form

$$A(z + \Delta z, t) = \begin{pmatrix} q_1 & -q_2^* \\ q_2 & q_1^* \end{pmatrix} A(z, t)$$

where q_1 and q_2 are matrix elements describes mode coupling and satisfies to equation $|q_1|^2 + |q_2|^2 = 1$.

In this paper, considered two known methods of DMD compensating [29]. One is the modes crossing (Fig. 1a) and other is the inserting of delay line (Fig. 1b). As noted earlier, DMD compensation were included on linear optical amplifiers. When modes crossing was used, the even number of amplification spans was chosen, and their length was assumed to be same.



Figure 1. DMD compensating by modes crossing (a) and inserting of delay line (b),
b) where MDM – mode division multiplexer; DL – delay line.

To compare the merits of the few-mode fiber optic links as in [19, 30], the concept of the FEC threshold was used. By the simulation results, the dependences of the BER for the each optical mode channel on the far end from the peak power at the fiber optic link input were built. Based on this curves the dynamic range was estimating, assuming that for BER below the FEC threshold, the signal at the reception is completely restored. The threshold value was assumed to be $BER = 4.7 \cdot 10^{-3}$ [30].

3. Results of simulation

In this paper, the simulation was performed for an optical signal with quadrature phase modulation (QPSK) with a symbol bit rate 28.5 Gbit/s with pulse shape 50%RZ, providing an information bit rate of 114 Gbit/s. The regeneration section consists from 10x100 km amplifying sections with total length of 1000 km. The average value of the delivery length of the optical cable was assumed equal to 5 km. An erbium optical amplifier was used for ideal compensation of optical path loss with 5 dB noise factor. The noise of the optical amplifier was modeled by additive white Gaussian noise and added to the signal at the end of each amplifier section. The two-mode fiber used for simulation supports the propagation of two modes LP_{01} and LP_{11} at the optical signal wavelength under the condition of equal mode excitation. The parameters of two-mode fiber are represented in Table 1.

Table 1. The parameters of two-mode fiber.

Mode type	LP_{01}	LP_{11}
Attenuation coefficient, dB/km	0.198	0.191
Chromatic dispersion coefficient, ps/nm/km	19.8	20.0
Chromatic dispersion slope, ps/nm ² /km	0.067	0.065
Differential mode delay, ps/m	-	- 0.2 ÷ 0.2
Effective mode spot area, μm^2	95	95

Simulations were performed for two schemes of DMD compensating either for chromatic dispersion compensating on the far end of the line or on LOAs. Figures 2 a, b show the simulation results for the case of chromatic dispersion compensating on the far end of the two-mode optical fiber communication link. The simulation results showed when chromatic dispersion compensating only on the reception, the DMD compensation on LOAs does not change the dynamic range.

Figures 3 a, b show the simulation results for case of chromatic dispersion compensating on LOAs. As shown by calculations, for the case of the chromatic dispersion compensation on the LOAs, of the DMD compensation on the LOAs causes an insignificant, but still an increase in the dynamic range. The increment was about 0.15 dBm. This suggests that DMD compensation and the chromatic dispersion compensation on denser maps can yield a significantly larger gain. Especially, if we take into account the effect of chromatic dispersion compensation on LOAs and the experience of group delay management in mode-division multiplexing systems [29].

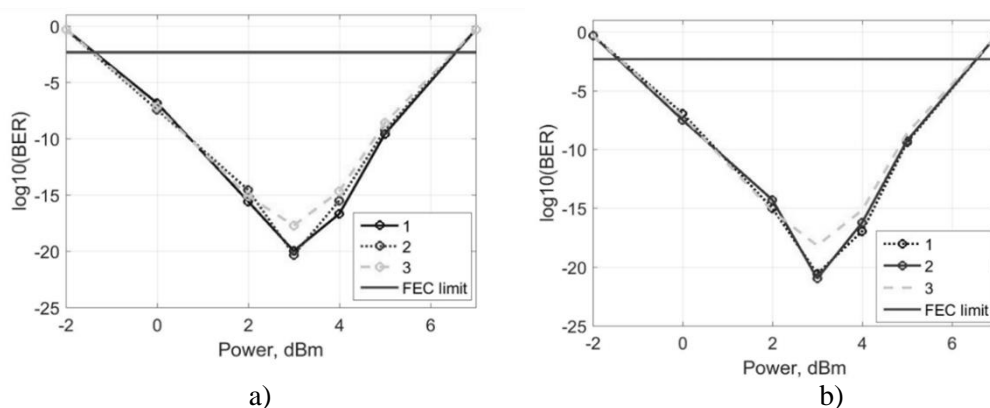


Figure 2. The dependence of the BER on the peak power at the input of a two-mode fiber-optic link with compensation of chromatic dispersion at the reception for the $LP_{01}(a)$ and $LP_{11}(b)$ modes (1 - without compensation DMD; 2 - DMD compensation on LOAs by modes crossing; 3 - DMD compensation on the LOAs with the delay line inserting).

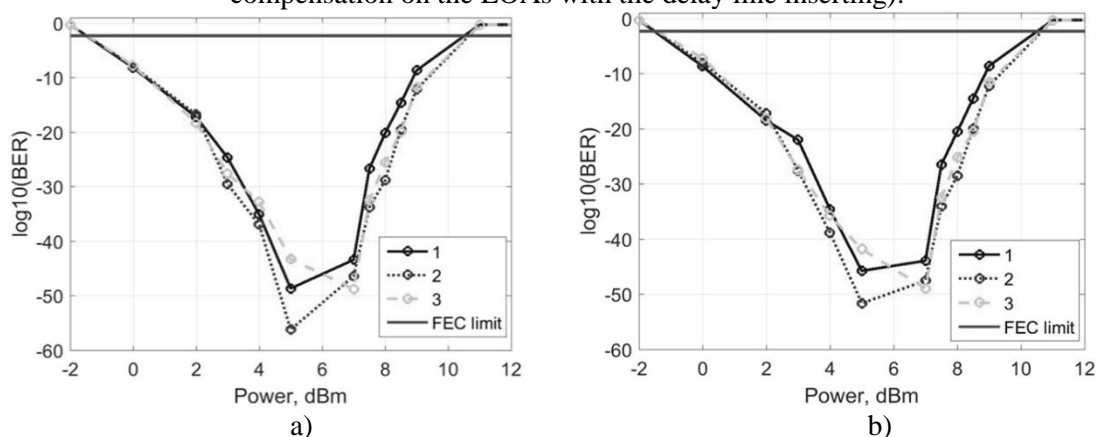


Figure 3. The dependence of the BER on the peak power at the input of a two-mode fiber-optic link with compensation of chromatic dispersion on the LOAs for the $LP_{01}(a)$ and $LP_{11}(b)$ modes (1 - without compensation DMD; 2 - DMD compensation on LOAs by modes crossing; 3 - DMD compensation on the LOAs with the delay line inserting).

4. Conclusion

An analysis of the simulation results for the long-haul two-mode fiber-optic communication line with DMD compensation on a LOAs, presented in this work showed following. For the chromatic dispersion compensation only at reception, there is no positive effect from DMD compensation on LOAs. But the slight increase in the dynamic range, about 0.15 dBm, for the case of chromatic dispersion compensation on LOAs, lets talk about the possible a more significant positive effect under chromatic dispersion compensating and DMD compensating on a dense maps.

5. References

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