Impact of the In-Line Dispersion-Compensation Map on Four-Wave Mixing (FWM)—Impaired Optical Networks

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Abstract—The impact of the dispersion-compensation map on four-wave mixing—impaired nonreturn-to-zero modulated wavelength-division-multiplexing systems is investigated. Dedicated worst-case scenarios are found analytically and confirmed by recirculating loop experiments.

Index Terms—Optical crosstalk, optical fiber communication, optical fiber nonlinearity, wavelength-division multiplexing (WDM).

I. INTRODUCTION

FOUR-WAVE mixing (FWM) is one of the dominating degradation effects in wavelength-division-multiplexing (WDM) systems with dense channel spacing and low chromatic dispersion on the fiber. If in a WDM system the channels are equally spaced, the new waves generated by FWM will fall at channel frequencies and, thus, will give rise to crosstalk. In case of full in-line dispersion compensation, i.e., 100% dispersion compensation per span, the FWM crosstalk becomes maximum since the FWM products add coherently in each span [1]. In this letter, for the first time to our knowledge, we demonstrate both analytically and experimentally that other in-line dispersion maps result in a worst case for FWM-impaired systems. In the analysis, only the nonlinear signal distortions due to FWM are taken into account.

II. ANALYTICAL MODEL AND EXPERIMENT SETUP

For the experiment, the following recirculating loop setup has been used (Fig. 1) [2]. Twenty nonreturn-to-zero (NRZ)-modulated 9.953-Gb/s channels have been spaced on a 50-GHz grid (1531–1538 nm). All channels had a parallel polarization at the loop input, which represents the worst-case situation. In the experiment, a predispersion-compensating fiber (DCF) has been incorporated in the loop (see Table I). Alternatively, full-in-line compensation (FOCS [3]) has been used (0 ps/nm in the first span, –6 ps/nm in the second span, and 0 ps/nm in the third span). No additional postcompensation was employed at the output of the loop because this does not affect the measured FWM power, which was outside of the signal spectrum. The booster amplifiers had an output power of 1 dBm/ch for all transmission fibers and –2 dBm/ch for the DCFs. The lengths of the three spans were 68, 68, and 64 km, respectively. The fiber parameters of the experiment are shown in Table I. The analytical model used for the assessment of the FWM degradation in this letter was based on the single span continuous-wave approximation in [4], which was extended to a multi-span transmission line incorporating amplifiers in [5]. The amplitude of an FWM mixing product at frequency \( \nu_m \) which is generated by waves \( i \), \( j \), and \( k \), can be calculated in the general case from the following [4]:

\[
A_{m;i,j,k}(l_1,l_2) = j \gamma \left( \frac{d}{3} \right) A_i(0) A_j(0) A_k(0) 
\cdot \int_{z=h_1}^{l_2} \exp(-jz) \exp(-j\Delta k z) dz
\]

where \( A \) is the amplitude of the envelope of the different waves, \( \gamma \) is the nonlinearity constant of the fiber, and \( \alpha \) the
and involves the propagation constant of the FWM products and is directly related to the amount of in-line residual dispersion per span

\( \Delta \beta = \beta_k + \beta_j - \beta_k - \beta_{jk} \)

\[= \frac{2\pi \lambda^2}{c_0} (f_i - f_k)(f_j - f_k) \left[ D - \frac{\lambda^2}{c_0} \left( \frac{f_i + f_j}{2} - f \right) \right] S. \]

(2)

To take into account the random nature of the modulated signal, three-tone products are weighted by a factor of 1/8 and two-tone products by a factor of 1/4. This comes from the probability in a pseudorandom binary sequence, which is 0.5 for a mark.

The behavior in Fig. 2 can be understood from the following scaling factor for FWM mixing power [1]:

\[ S_{FWM} = \left| \sum_{n=1}^{N} \exp(-j(m-1)\Delta \psi) \right|^2 \]

\[= \sin^2 \left( \frac{N \Delta \psi}{2} \right). \]

(3)

N defines the total number of spans. \( \Delta \psi \) involves the propagation constant of the FWM products and is directly related to the amount of in-line residual dispersion per span

\[ \Delta \psi = \Delta \beta_{NZDSF} \cdot L_{NZDSF} + \Delta \beta_{DCF} \cdot L_{DCF} \]

\[\cong D_{NZDSF} \cdot L_{NZDSF} + D_{DCF} \cdot L_{DCF}. \]

(4)

The phase mismatch between the different channels is described by \( \Delta \beta \). Equation (3) results in a worst-case scenario for the commonly used DUCS [3] of approximately 

-50 ps/nm/span because, in this case, the denominator gets very small. The optimum can be achieved for an undercompensation of \( \sim 40 \) ps/nm/span when the numerator becomes very small (compare Figs. 2 and 3). Please note that the graph depicted in Fig. 3 is symmetric to the y axis. This means that in-line undercompensation and overcompensation have the same impact.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In the experiment, the FWM power was measured outside of the signal spectrum with an OSA. For this purpose, the center channel was omitted so that at this position solely the FWM power could be measured (see inset in Fig. 4). The FWM power is considered as a figure of merit for the signal degradation because it will lead to crosstalk whenever it falls directly onto the signal channel. In Figs. 2 and 4, the ratio of the signal peak power to the FWM peak power is plotted on the ordinate.

For an undercompensation of \( \sim 50 \) ps/nm/span, it is shown that the increase of the FWM power with span count is comparable to the full-in-line compensation case (compare Figs. 2 and 4).
and 4). Note that this behavior is found for an average undercompensation of \(-50\) ps/nm/span. From Fig. 3, it can be seen that the worst-case degradation appears at \(-56\) ps/nm/span. The amount of undercompensation does not necessarily exactly meet this value in each individual span. Also the span length may vary on a span-by-span basis. Only the absolute amount of undercompensation per span is the relevant parameter. This is why the results of this experiment can also be applied to networks deployed in the field where the dispersion map may not be as strict as in laboratory experiments. From these observations, conclusions can also be drawn regarding the impact of dispersion slope mismatch. The influence of slope mismatch is similar to a statistical variation of the span dispersion [7]. If the slope mismatch is only a few picoseconds per square nanometer, as in the experiment, the results are comparable to the ones obtained for a perfectly compensated system (compare Fig. 4). In general, slope mismatch will lead to a reduction of the main peaks of the resonances [7].

Fig. 4 also shows the calculated values from analytical equations (1) for comparison. It can be seen that an undercompensation of \(-40\) ps/nm/span shows a clear advantage compared to other in-line residual dispersion values. The discrepancy between the analytical curve and the measured one stems mainly from the fact that the DCFs did not match the exact FOCS and DUCS compensation maps, but varied slightly. Also, the DCF nonlinearity was neglected in the analytical model. Theoretically, it is possible to design an in-line dispersion-compensation map in such a way that the FWM power decreases at certain span counts because different FWM products may annihilate each other (compare Figs. 2 and 4). This, however, requires an almost perfect dispersion slope match. In the case of a higher number of channels, this becomes more difficult because the edge channels have a relatively high frequency separation from the center channel and the mismatch in dispersion slope leads to a walkoff from span to span with regard to the center channel.

In the experiment, a 4-nm spacing existed from the edge to the center channel leading to a dispersion mismatch of the edge channels of approximately \(\pm 8\) ps/(nm \cdot span). Note that in Fig. 5 only the center channel is considered. Generally, the crosstalk of the edge channels and the center channel will not be the same. At the same time, the edge and the center channels have a common optimum dispersion map.

IV. CONCLUSION

In this letter, the impact of varying amounts of in-line dispersion compensation is investigated. It is demonstrated that distributed undercompensation does not necessarily show a significant improvement compared to full-in-line compensation. Conditions for worst-case scenarios have been identified. It has been indicated that such a scenario is represented for an undercompensation of \(-50\) ps/nm/span. This case is almost as bad as full-in-line dispersion compensation, where the amplitudes of all FWM products add up in phase. This finding is especially important because an undercompensation of \(-50\) ps/nm/span optimizes SPM- and XPM-impaired systems and is a value commonly used in optical networks. However, for systems with very low dispersion fibers, which are FWM-limited, other in-line-residual dispersion values should be chosen (e.g., an undercompensation of \(-40\) ps/nm/span).

REFERENCES