Suppression of Fiber Nonlinearities by Appropriate Dispersion Management

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***Abstract*—A specific fiber dispersion management is proposed allowing the simultaneous suppression of linear dispersion penalties and of degradations arising from parametrical fiber nonlinearities. For the proposed dual dispersion configuration (DDCON) the number of optical channels that can be transmitted over 1000 km at a bit rate of 2.5 Gb/s is only limited by the available optical amplifier bandwidth.**

I. Introduction

The realization of high capacity optical communication systems necessitates the suppression of linear and nonlinear system deterioration. While the accumulation of chromatic dispersion and optical amplifier noise can be understood quite intuitively, the determination of fiber nonlinearities requires a much more subtle analysis. One can distinguish between two categories of nonlinear effects by their sensitivity to fiber dispersion: The parametrical processes, such as four-photon mixing (FPM), self-phase modulation (SPM), and cross-phase modulation (XPM), can be influenced in wide ranges by the design of fiber dispersion. In contrast the inelastic stimulated Raman- (SRS) and Brillouin- (SBS) scattering processes are almost independent of dispersion.

In the following we will show how the parametrical nonlinearities can be suppressed by a clever system design.

II. Description of the Analyzed Configuration

The analysis is carried out for a frequency-shift-keying (FSK) direct-detection system as shown in Fig. 1. At the transmitter N laser diodes emitting at different optical frequencies are frequency-modulated at a bit rate of 2.5 Gb/s. The signals are multiplexed into an optical fiber and transmitted over 1000 km. Optical amplifiers with equal gain G are spaced by Δ_{OA} and used to compensate for the fiber attenuation, so that $G = L^{-1}$, where L is the loss between two consecutive amplifiers. At the receiver a first optical filter serves for channel selection and a second, Mach–Zehnder type optical filter is used for demodulation. Finally, the signal is detected by a dual-APD configuration.

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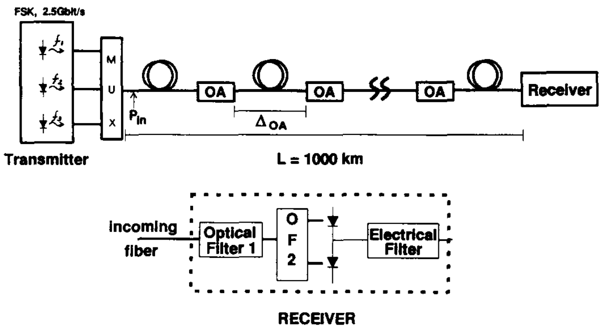

Fig. 1. Analyzed configuration (FSK/direct-detection system).

III. Nonlinear Performance of a System With Dispersion-Shifted Fibers

Motivated by a purely linear system analysis, most of the realized systems use dispersion-shifted fibers (DSF's) for transmission, where the chromatic dispersion coefficient $D_\lambda \ll 1$ ps/(km · nm). In this section we analyze the nonlinear four-photon mixing performance of a system with a fiber where $D_\lambda = 1$ ps/(km · nm). As will be obvious later, this configuration clearly outperforms systems with lower (zero-) dispersive fibers.

Using the results in [2], we plotted in Fig. 2 the maximum optical input power per channel P_{in} (see Fig. 1) leading to a 1 dB FPM-penalty as a function of the frequency spacing of three equidistant spaced optical channels. The amplifier spacing has been chosen $\Delta_{OA} =$ 25 km. The solid lines are valid for homogeneous dispersion [$D_\lambda = 1$ ps/(km · nm)] along the whole transmission distance.

First we can state the tendency that an increase in channel spacing leads to an increase in tolerable input power, which can be explained by the reduction in phase matching of the interacting photons. Furthermore, a structure can be observed, which is dependent on the specific optical amplifier spacing: In the cases where the nonlinear fields generated along the different fiber spans interfere constructively at the receiver, the tolerable power is very low (worst-cases). Additionally, there are cases where the fields completely cancel out each other. Finally, we can find spacings with incomplete cancellation. The latter are technically accessible and their optima will be considered in the following (see Fig. 2).

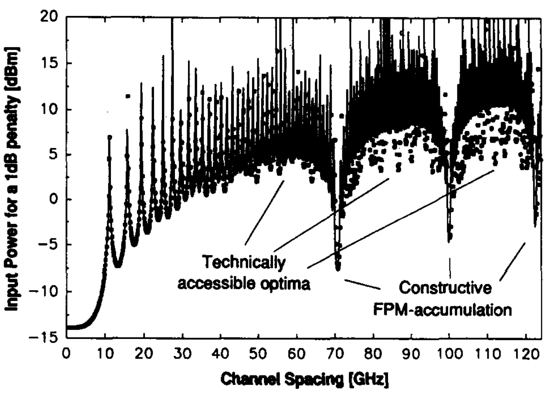

Fig. 2. Maximum optical input power per channel as a function of channel spacing for a 3 × 2.5 Gb/s, 1000 km conventional FSK/DD system with 25 km EDFA spacing, using dispersion shifted fibers.

In real systems, the chromatic dispersion will fluctuate along transmission distance. The resulting power requirements for 10%-deviation from the nominal value [$D_\lambda = 1$ ps/(km · nm)] are indicated by the square-symbols in Fig. 2. As can be seen, only slight changes occur for the worst-cases whilst the optima are considerably affected, stating that the cancellation of different nonlinear components is now more incomplete.

IV. Description of the Dual Dispersion Configuration

From nonlinear system considerations it is obvious that a clever dispersion management has to be used in order to meet the following requirements:

- low overall dispersion,
- low nonlinear photon interaction efficiency and
- high stability with respect to chromatic dispersion fluctuations.

Those criteria can be satisfied with the dual dispersion configuration (DDCON) which is explained in Fig. 3: In a conventional system with dispersion-shifted fibers the overall dispersion increases with increasing system length. The local slope is given by the fiber chromatic dispersion and consequently very low. In contrast, we propose to use two fibers with relatively high chromatic dispersions. It has to be pointed out that, compared to the zero-dispersion fibers, a dispersion coefficient in the order of a few ps/(km · nm) may already be considered high. For ultimative bandwidth exploitation, however, *i.e.*, closest channel allocation, four-photon mixing necessitates the highest possible dispersion. For systems with amplifier spacings of $\Delta_{OA} = 25$ km and channel spacings in the order of 25 GHz, a positive dispersion of $D_{\lambda_+} \approx 17$ ps/(km · nm) and a negative dispersion of $D_{\lambda_-} \approx -15$ ps/(km · nm) would be an appropriate choice.

The physically relevant parameter is the effective channel separation s_{eff}, which is given by [1]

$$s_{eff} = D_\lambda \cdot 2\Delta f^2 \tag{1}$$

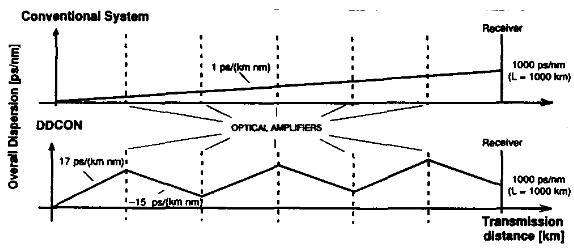

Fig. 3. Dependence of total system dispersion on system length (a) for a conventional system with dispersion shifted fibers (b) for the dual dispersion configuration.

for a three-channel system, where Δf is the frequency spacing between two neighboring channels. For the above values, this parameter yields approximately $s_{eff} \approx 1.3$ (ps · nm/km) for each fiber segment (1 nm ≈ 125 GHz at $\lambda = 1.55$ μm). However, an increase of Δ_{OA} above the assumed 25 km results in an enhanced amplifier noise, which reduces the window of operability [2]. Therefore a corresponding increase in s_{eff} by increasing the channel spacing may be necessary. In any case multichannel systems, where s_{eff} is about one order of magnitude higher [$s_{eff} \approx 10$ (ps · nm/km)] will not exhibit any four-photon mixing limitation.

Finally we consider the stability to dispersion fluctuations. In a system with high first-order dispersion coefficient, only the fluctuations in first-order dispersion are relevant: As we can see from a comparison of Figs. 2 and 4, an increase in fiber dispersion yields an increase in the number of constructive interference cases (worst-cases). In particular, it turns out that there do no longer exist any technically accessible optima in the DDCON-scheme. Thus maximum optical input power is not determined by the cases of incomplete cancellation of the generated nonlinear fields as in the case of the constant dispersion fiber but rather by the interpolation of the worst-case values (constructive resonances). As we have stated above, the worst-cases are hardly affected by dispersion fluctuations. From this we conclude that DDCON is stable against variations in first-order group velocity dispersion so that all three requirements are met.

V. Nonlinear Multichannel Performance of DDCON

An important parameter of the dual dispersion configuration is the length along which the dispersion is constant in a dispersion tailored system L_{con}, which has been chosen in Fig. 3 to be equal to the amplifier spacing. Although this configuration already suppresses four-photon mixing by several dB's, it turns out that an additional gain can be obtained by increasing the segment length. For a transmission length of 1000 km, the maximum length would be $L_{con} = 500$ km. For this case and three optical channels we plotted in Fig. 4 the maximum input power per channel for a 1 dB penalty as a function of the channel spacing. The amplifier spacing has been chosen

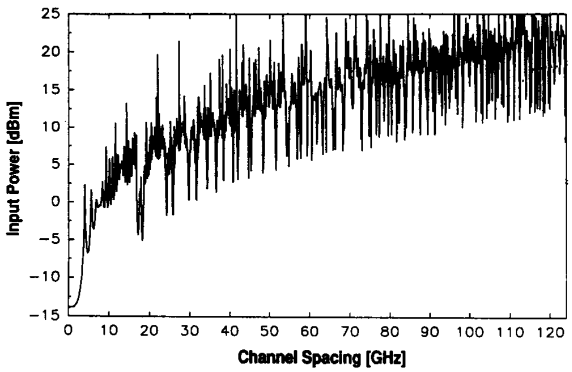

Fig. 4. Maximum optical input power per channel as a function of channel spacing for a 3 × 2.5 Gb/s, 1000 km FSK/DD system with 25 km EDFA spacing, using the dual dispersion configuration.

$\Delta_{OA} = 25$ km. Again, we assumed a 10% fluctuation from the nominal dispersion for each of the two constant dispersion segments. From a comparison with Fig. 2 one can see that the nonlinear interaction efficiency has been considerably reduced, e.g., the input power gain at the channel spacing of $\Delta f = 70$ GHz is about 15 dB. The above stated improvement resulting from an increase in L_{con} can be intuitively understood, if we take into account that a (nearly) zero-dispersion fiber, for which the nonlinear interaction efficiency is very high, can be interpreted as a concatenation of positive and negative dispersion segments having an incremental length $L_{con} - > 0$. Due to the transition from zero-dispersive to a constant (highly) dispersive fiber with increasing L_{con} we expect the tolerable input power level to increase.

In Fig. 5 we plotted for $\Delta_{OA} = 25$ km the tolerable input power per channel as a function of the number of channels. The solid and the broken lines are for 50 GHz and for 25 GHz, respectively. In addition to the upper input power limit, the minimum input power requirement introduced by the optical amplifier cascade is also indicated [2]. We can see that the number of optical channels is limited to about $N = 5$ for $\Delta f = 25$ GHz and to about $N = 10$ for $\Delta f = 50$ GHz in a system with dispersion-shifted fibers, whilst no limitation exists in the case of the dual dispersion configuration (except for the optical amplifier bandwidth economy).

Let us now discuss the channel-dependence of DDCON in detail. As can be seen from Fig. 5, the improvement of DDCON with respect to the conventional system increases with increasing number of channels; in a three-channel system with $\Delta f = 50$ GHz, for example, this DDCON-gain $g_{DDCON} \approx 6$ dB, whilst it increases to about $g_{DDCON} \approx 14.5$ dB in a 20-channel system. This results from the saturation behavior of the power versus number of channels-plot: By adding equidistantly-spaced optical channels to a three-channel system, one first increases the number of nonlinear four-photon mixing components that deteriorate the signal-to-noise ratio (SNR). Thus, the tolerable input power per channel will decrease. With further increase in number of channels, however, the additional degradation in SNR caused by the latter additional channels will become less significant, since the effective channel separation is now much higher (the parameter $2\Delta f^2$ in (1) has to be replaced by $(N + 1)/2 \cdot \Delta f^2$, where N is the number of optical channels). Finally, the nonlinear FPM-component will be insensitive to any additional channel, leading to the saturation of the tolerable optical input power. Due to the higher dispersion coefficient, this saturation level is reached for DDCON at much lower numbers of channels than in the conventional system. In particular, DDCON is already saturated while the acceptable power level still decreases in the conventional system, causing an increasing DDCON-gain with increasing number of channels. When the number of channels reaches a certain critical value determined by the difference in dispersion between the two schemes and the used channel spacing Δf, the DDCON-gain becomes constant.

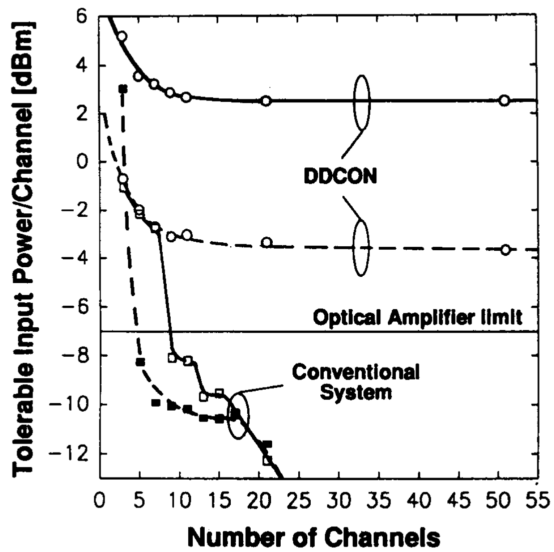

Fig. 5. Tolerable input power per channel as a function of the number of channels for a conventional system and for DDCON. The solid lines are for 50 GHz channel spacing and the broken lines for 25 GHz channel spacing.

VI. Impact of Self- and Cross-Phase Modulation

Once the fiber four-photon mixing has been suppressed by DDCON, the nonlinear self-phase modulation (SPM) and cross-phase modulation (XPM) [4] may still degrade the linear system performance. However, the specific DDCON parameters (positive and negative dispersions D_{λ_+}, D_{λ_-}, constant dispersion segment length L_{con} and optical channel spacing Δf) can be optimized to yield good system performance with respect to all three parametrical effects: It is well known that only a modulation of the field envelope can act as a source for SPM-induced system-degradations. Since in a frequency (shift-keying) modulated system the envelope is constant, the only modulation can arise from dispersions-induced FM to AM conversion. By adjusting either the fiber dispersion parameter (to lower values) or by reducing the length L_{con} excessive FM to AM conversion can be prevented. On the other hand, it has been shown that penalties due to XPM can be suppressed by increasing the channel spacing, so that the interaction length of the bits of two different channels is short in comparison to the optical amplifier spacing [5]. In consequence FPM, SPM, and XPM can be successfully suppressed in DDCON.

VII. Conclusion

We have shown that the capacity of future multichannel transmission systems is significantly limited by fiber nonlinearities when zero-dispersion fibers are employed. In contrast, one can achieve complete suppression of parametrical nonlinearities in long haul multichannel systems by using the dual dispersion configuration.

Acknowledgments

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A Frequency Calibration Method for Multilocation Optical FDM Networks

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***Abstract*—A simple laser frequency calibration method is proposed for optical frequency-division-multiplexing communications networks where users are at remote locations. We calibrate the frequency of a transmitter laser by tuning it to a resonant peak of a Fabry–Perot etalon and determining the mode number of the resonant peak. We use a distributed frequency reference and a local Fabry–Perot etalon whose cavity length is slightly changed during the measurement. This method provides a high measurement accuracy with a cavity length change of less than 5%.**

I. Introduction

Optical frequency-division-multiplexing (FDM) technology has gained considerable attention since it offers access to the vast optical bandwidth of single-mode fibers. The advent or erbium-doped fiber amplifiers renders it more attractive because a fiber amplifier can simultaneously amplify a number of optical carriers. As erbium-doped fiber amplifiers have a finite gain bandwidth of about 30 nm, an ordinary wavelength-division-multiplexing (WDM) network with a channel spacing of 2 nm can support only about 15 wavelengths. In an optical FDM network, however, 400 channels are allowed within the gain bandwidth of fiber amplifiers for a channel spacing of 10 GHz (0.8 nm). As the frequency of a semiconductor laser is not stable under free-running conditions due to changes of temperature and injection current and possible aging, laser frequency stabilization and management are very important for optical FDM networks where users are at different locations. There has been several papers on frequency stabilization in multilocation optical FDM networks [1]–[3]. This paper addresses laser frequency calibration in such networks. In an optical FDM network, a transmitter laser must be tuned to and stabilized at its designated frequency. Since the laser at the user location can be turned on at any time with any lasing frequency, it must be frequency-calibrated before being connected to the network in order to avoid interference to other channels. That is to say, the calibration should be done locally. The frequency can be calibrated by using a high-accuracy optical wavelength meter [4]. This, however, is not cost-effective for a multilocation network. Another method is to sweep the laser frequency from a reference to the designated frequency and count the number of resonances of a Fabry–Perot etalon that it passes. This is also not realistic because the continuous tuning range of a semiconductor laser is only a few nanometers which is not large enough to cover the whole bandwidth of fiber amplifiers. In this paper, we propose a simple laser frequency

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