Weighted nonlinear phase shift with group velocity dispersion to assess the nonlinear penalty in C+L band long-haul fiber optical amplified transmission link

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To assess the penalty due to nonlinear effect in C+L band long-haul optical amplified transmission link, a new parameter of modified nonlinear phase shift (ϕ_{D}) is proposed, which is the accumulated nonlinear phase shift weighted by a normalized group velocity dispersion (GVD). Based on the numerical simulation result of broadband long-haul hybrid Raman/erbium-doped fiber amplified transmission line, it is validated that ϕ_{D} is more reasonable and suitable than the previous proposed nonlinear phase shift (ϕ_{NL}) for broadband applications.

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In broadband wavelength division multiplexing (WDM) system, the nonlinearity impact is important for the transmission performance. In the system where only erbium-doped fiber amplifier (EDFA) is employed, the input signal power can be used to assess the nonlinearity penalty. But in those systems adopting distributed fiber Raman amplifiers (DFRAs), the input signal power is no longer valid, because the signal power distribution along the transmission fibers can be varied very much depending on the DFRA. In previous work[1,2], the accumulated nonlinear phase shift (ϕ_{NL}) was considered as a criterion based on the viewpoint that the same ϕ_{NL} would induce the same penalty. However, this is true only for single channel or narrow bandwidth. It is well known that, in an intensity modulation direct-detection (IM-DD) system, the nonlinear phase fluctuation would be translated into intensity noise (IN) via the accumulated residual chromatic dispersion. In a long-haul transmission line, nonlinearity phase shift would occur at any fiber section, and its impact would act through the residual chromatic dispersion accumulated over the rest transmission fiber, so dispersion management is required to suppress both the nonlinearity and waveform distortion. Although the same chromatic dispersion compensating ratio could be achieved for each WDM signal channel over $\sim$ 100-nm wavelength range by applying dispersion compensating fiber (DCF) with dispersion-slope compensating, the residual dispersions along the transmission fiber are still wavelength dependent. Therefore, a criterion that takes the wavelength-dependent dispersion into account is necessary, especially in the broad C+L band systems.

In this letter, based on the simplified theoretical analysis, a new criterion of modified nonlinear phase shift ϕ_{D} is proposed, which is the accumulated nonlinear phase shift weighted by a normalized group velocity dispersion (GVD) factor. It is demonstrated by numerical simulation that ϕ_{D} is more reasonable and suitable for assessing nonlinear penalty in the WDM transmission system.

Considering a WDM IM-DD transmission system employing dispersive optical fiber, the single-sided relative intensity noise (RIN) added on a considered channel at wavelength λ_0 by a random binary intensity modulated channel at wavelength λ_m is given by[3]

$$\sigma_m^2(\omega) = 2\left|H_m(\omega)\right|^2 \left\langle P_m\right\rangle^2 S_{\mathrm{mod}}(0,\omega), \tag{1}$$

where $H_m(\omega)$ is the transfer function that represents the nonlinear effect of the fiber, $\langle P_m\rangle$ is the time average input power of the channel at λ_m, and $S_{\mathrm{mod}}(0,\omega) = \frac{1}{4T}\left|\widetilde{F}_{\mathrm{mod}}(\omega)\right|^2 + \frac{1}{4T^2}\sum\limits_{k=-\infty}^{\infty}\left|\widetilde{F}_{\mathrm{mod}}(\frac{k}{2\pi T})\right|^2\delta(\omega-\frac{k}{2\pi T})$ is the normalized spectral density of the channel at λ_m (divided by average input power). T is the bit period and $\widetilde{F}_{\mathrm{mod}}(\omega)$ is the Fourier transform of single pulse, which is dependent on the modulation format and chirp character of input signal.

For a real transmission link, $H_m(\omega)$ is complicated. In order to get clear physical points, here only one single span is considered. By assuming continuous-wave channel at λ_0 and undistorted modulated channel at λ_m, the $H_m(\omega)$ of cross phase modulation (XPM) can be calculated through small signal analysis as[4]

$$H_m^{\mathrm{XPM}}(\omega) = 4\gamma_0 \int\limits_0^L \exp\left[(-\alpha + j\omega d_m)z\right] \times \sin\left[-\omega^2\beta_{20}(L-z)\right]\mathrm{d}z, \tag{2}$$

where γ_0 and β_{20} are the nonlinear coefficient and GVD at λ_0, α and L are loss coefficient and length of the fiber, $d_m = \int_{\lambda_m}^{\lambda_0} D(\lambda)\mathrm{d}\lambda$ is the walk-off parameter between the channels at λ_0 and λ_m. The exponential term in the integral of Eq. (2) represents a walk-off effect, which means that the XPM-induced noise decreases dramatically as the channel separation increasing related to d_m. The sinusoidal term presents that the phase fluctuation is translated to IN by the residual chromatic dispersion accumulated over the rest transmission fiber. So the XPM noise must be wavelength-dependent due to wavelength-dependent dispersion of β_{20}.

Equation (2) can be also used to describe the self phase modulation (SPM) effect by setting $d_m = 0$ and change the product factor from 4 to 2[5]:

$$H_0^{\mathrm{SPM}}(\omega) = 2\gamma \int_0^L \exp(-\alpha z)\sin\left[-\omega^2\beta_{20}(L-z)\right]\mathrm{d}z. \quad (3)$$

Similar to XPM noise, the SPM effect is also related to the wavelength-dependent dispersion.

Generally, the signal channels are nearly de-correlated, so the total RIN power on the considered channel at the receiver is the sum of the contribution from all the modulation frequencies and all signal channels:

$$\sigma_{\mathrm{RIN}}^2 = \sum_{m=1}^{N}\left(\frac{1}{2\pi}\int_0^{\infty}\sigma_m^2(\omega)\left|T_{\mathrm{e}}(\omega)\right|\mathrm{d}\omega\right), \quad (4)$$

where $|T_{\mathrm{e}}(\omega)|$ is the transfer function of electrical filter at the receiver, N is the number of signal channels in the WDM system.

In fact, due to the walk-off effect, only the channels within a narrow bandwidth $\Delta\lambda$ around λ_0 have to be considered. In G.655 fiber, $\Delta\lambda$ is about 2 nm[3], and in G.652 fiber, it is even smaller because of a higher dispersion coefficient. Within this narrow bandwidth, the walk-off effect can be neglected by setting $d_m = 0$ and the average power of each channel can be treated as equal ($\langle P_m\rangle = \langle P_0\rangle$) within the wavelength range of $\lambda_0 - \Delta\lambda \leq \lambda_m \leq \lambda_0 + \Delta\lambda$. Considering the fact that the channel power is mainly distributed within a limited frequency range and β_2 is small, we have $\sin(\omega^2\beta_2 L) \approx \omega^2\beta_2 L$. Meanwhile, the approximation of $\alpha L > 1$ can be adopted since the fiber length L is usually long. Then the transfer function for SPM and XPM can be expressed by a same formula:

$$|H_m(\omega)| = n\left|\frac{\gamma_0}{\alpha}\beta_{20}(L - L_{\mathrm{eff}})\omega^2\right|, \quad (5)$$

where $n = 1$ or 2 represent the product factor for SPM or XPM, respectively, $L_{\mathrm{eff}} = \frac{1-\exp(\alpha L)}{\alpha}$ is the fiber effective length. As the result, the total RIN power can be derived as

$$\sigma_{\mathrm{RIN}}^2 = \left[\frac{\langle P_0\rangle\gamma_0}{\alpha}\cdot\beta_{20}(L-L_{\mathrm{eff}})\right]^2\frac{1+4N_{\mathrm{XPM}}}{\pi} \times\int_0^{\infty}S_{\mathrm{mod}}(0,\omega)\omega^2\left|T_{\mathrm{e}}(\omega)\right|\mathrm{d}\omega, \quad (6)$$

where N_{XPM} is channel number within the bandwidth of $\Delta\lambda$. The integral in right hand side represents the effect of modulation format, chirp character and response of electrical filter. Generally, the transmitted and received conditions of each signal channel can be treated as the same, so the RIN power is the only related nonlinear process. From Eq. (6), this process can be physically understood as that the nonlinear phase fluctuation of SPM and XPM occurs only within the range of the first $L_{\mathrm{eff}}\left(\frac{\langle P_0\rangle\gamma_0}{\alpha}\right)$, and then is translated into IN by GVD in the rest part of the fiber ($\beta_{20}(L-L_{\mathrm{eff}})$).

When considering a transmission link consisting of different types of fiber (such as SMF and DCF) with various signal distributions, the term of $\frac{\langle P_0\rangle\gamma_0}{\alpha}$ should be replaced by the accumulated nonlinear phase shift $\phi_{\mathrm{NL}} = \int\gamma(z)P(z)\mathrm{d}z$ as shown in Ref. [2]. To consider further the GVD effect, ϕ_{NL} should be weighted by β_2 so that a new parameter of modified $\phi_{\mathrm{D}}(\lambda) = \frac{\beta_2(\lambda)}{\overline{\beta_2}}\times\phi_{\mathrm{NL}}(\lambda)$ is proposed. Here, both of the GVD ($\beta_2(\lambda)$) and nonlinear phase shift ($\phi_{\mathrm{NL}}(\lambda)$) at wavelength λ are considered. For keeping the dimension of new parameter the same as a phase shift and easily comparing with ϕ_{NL}, the product of $\beta_2(\lambda)\times\phi_{\mathrm{NL}}(\lambda)$ is normalized by the average GVD over all the channels in transmission fiber ($\overline{\beta_2}$). So if only one channel is considered, ϕ_{D} equals ϕ_{NL}.

It should be discussed that Eq. (5) is obtained under the assumption that the input channel power in bandwidth of $\Delta\lambda$ is equal. This assumption is valid for most applications even if Raman amplification is applied, since the input channel power and gain/loss distribution along the fiber are nearly equal in such a narrow bandwidth. During the derivation, the change of wave envelope along the fiber is neglected, which is also valid for most WDM terrestrial systems with dispersion periodically compensated. But for the case that the change of wave envelope cannot be neglected, ϕ_{D} may not be perfect and more consideration may be needed.

To validate ϕ_{D} as an assessing criterion, a group of numerical simulation has been carried out. The system arrangement is shown in Fig. 1, which is a typical WDM 30 × 100 km single mode fiber (SMF) transmission link amplified by hybrid Raman/erbium-doped fiber amplifier (HFA). The distributed fiber Raman amplifier was pumped backward (B-DFRA) or bi-directionally (Bi-DFRA). The dispersion was compensated before (pre), along (inline) and after (post) the link. The transmitter consists of 160 channels over C-band (1529 – 1560.6 nm) and L-band (1571.8 – 1603.4 nm) with the interval of 0.4 nm. All the channels were parallel in polarization. The channels were modulated by 50% return-to-zero (RZ) 64-bit pseudo-random 10-Gb/s sequence, and decorrelated by introducing a random delay. The Raman gain coefficient and fiber loss for transmission fiber and DCF were obtained from measurement, as shown in Fig. 2. The nonlinear coefficients are 1.2 and 5.7 $\mathrm{kW^{-1}\cdot km^{-1}}$ for SMF and DCF, respectively. The dispersion coefficients $D(\lambda)$ for SMF at each wavelength were calculated by three-order Sellmeier equation and the DCF was assumed fully matched with SMF in both dispersion and the slope in wavelength range of 1528 – 1604 nm as shown in Fig. 3.

Five pump wavelengths at 1423, 1433, 1443, 1463, and 1493 nm were used to achieve about 75-nm flat gain.

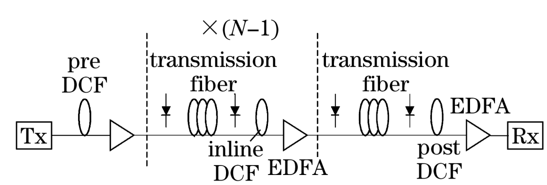

Fig. 1. Investigated system arrangement. Tx: transmitter; Rx: receiver.

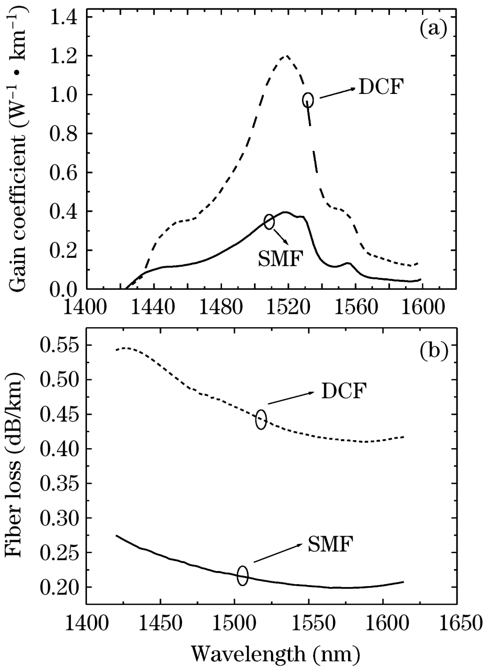

Fig. 2. (a) Raman coefficient and (b) fiber loss spectra of SMF and DCF used in simulation.

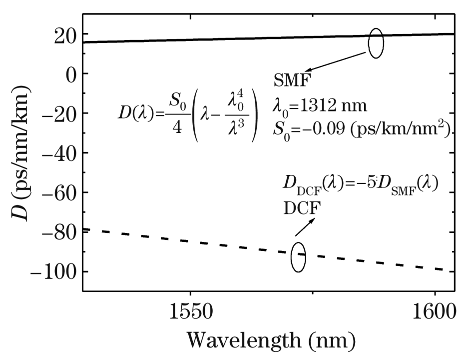

Fig. 3. Dispersion coefficient spectra of SMF and DCF used in simulation.

For Bi-DFRA, the powers at the shorter four wavelengths were partially set forward to achieve both flat noise figure and gain spectrum. The simulation was started from a given net gain of DFRA and input channel power, and then the powers for individual pump wavelengths were optimized by the procedure similar as Refs. [6,7]. After the pump combination was determined, the power evolution of signal, pump and amplified spontaneous emission (ASE) along the fiber was calculated by solving a set of coupling equations. The gain spectrum of EDFA was determined by setting the total span loss compensated perfectly and the noise figure of EDFA was assumed as 4.5 dB for each channel. To find out the amplitude of all the channel waves, split-step Fourier method was applied to solve nonlinear Schrödinger equation (NLSE). Here the crosstalk of pump-to-signal and signal-to-signal is neglected for simplicity. Finally, the average Q-factor for 8 patterns was calculated with optimized decision voltage level[8], and the calculated Q-factor spectrum was smoothed by 10-point moving average to avoid the random error. The optical filter and electronic filter at receiver were set as 50 GHz and 7.5 GHz, respectively. To evaluate the system performance, a Q-factor considering only the optical signal-to-noise ratio (OSNR) is also calculated as the reference. The result considering both the nonlinear effect and ASE was compared with the reference, and the absolute difference was defined as the nonlinearity penalty.

The average net gains for DFRA were set as −14, −8, and −2 dB while the input channel power varied from −12 to 5 dBm/ch for B-DFRA+EDFA (B-HFA) and from −12 to −1 dBm/ch for Bi-DFRA+EDFA (Bi-HFA) in step of 1 dB, respectively. The length of inline-DCF was set as 20 km to compensate completely the 100-km SMF. Since the length of pre-DCF is less sensitive, it was set at constant value of 10 km (50% inline-DCF). The post compensation was optimized for each channel, each gain level and input channel power separately.

Figure 4 shows the calculated Q^2 penalty versus $\phi_{\rm NL}$ for both B-DFRA and Bi-DFRA. To be clear, only the data for channels of 1533 and 1599.4 nm are shown. In the figures, the curves for the same channel almost merge together, which is consistent with the result in Ref. [2]. But, there is a significant difference between the longer and shorter signal wavelengths with higher penalty for longer wavelength, when $\phi_{\rm NL}$ becomes large. By taking $\phi_{\rm D}$ as x-coordinate, the data in Fig. 4 are re-plotted and shown in Fig. 5. Obviously, the curves of two channels are much closer than those shown in Fig. 4. The results show that $\phi_{\rm D}$ is more reasonable and suitable as a criterion to assess the system performance, especially for broadband multi-channel cases.

To assess the nonlinear penalty by taking the wavelength-related dispersion coefficient into account, a new modified nonlinear phase shift $\phi_{\rm D}$ was proposed

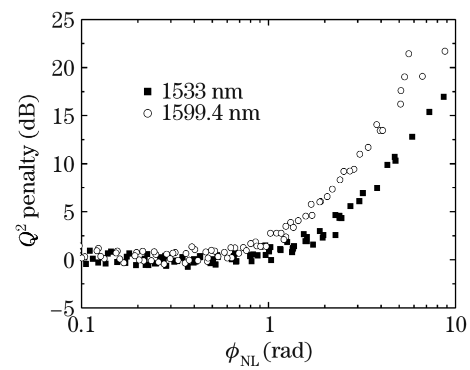

Fig. 4. Calculated Q^2 penalty versus $\phi_{\rm NL}$ after 30 spans transmission.

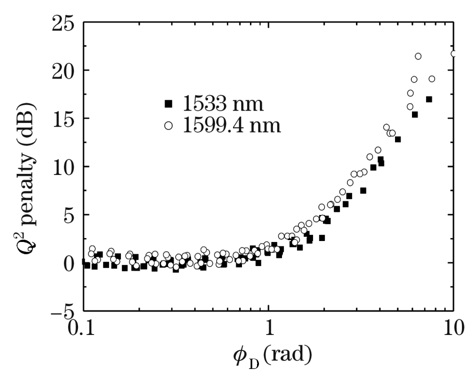

Fig. 5. Calculated Q^2 penalty versus $\phi_{\rm D}$ after 30 spans transmission.

based on the theoretical analysis. Via the numerical investigation on a 3000-km, 160-channel transmission line with hybrid DFRA+EDFA amplification, it is confirmed that the proposed ϕ_{D} is more reasonable and suitable as a criterion to assess the nonlinearity penalty for broadband terrestrial WDM systems.

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References

1. A. Carena, V. Curri, and P. Poggiolini, IEEE Photon. Technol. Lett. **13,** 1170 (2001).
2. J.-C. Antona, S. Bigo, and J.-P. Faure, in *Proceedings of Optical Fiber Communucation Conference (OFC) 2002* **70,** 365 (2002).
3. Z. Jiang and C. Fan, J. Lightwave Technol. **21,** 953 (2003).
4. G. Bellotti, M. Varani, C. Francia, and A. Bononi, IEEE Photon. Technol. Lett. **10,** 1745 (1998).
5. Y. Frignac, J.-C. Antona, and S. Bigo, in *Proceedings of Optical Fiber Communucation Conference (OFC) 2004* 536 (2004).
6. V. E. Perlin and H. G. Winful, J. Lightwave Technol. **20,** 250 (2002).
7. Z. Tong, H. Wei, and S. Jian, Opt. Commun. **217,** 401 (2003).
8. C. J. Anderson and J. A. Lyle, Electron. Lett. **30,** 71 (1994).