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Phase Noise Monitor and Reduction by Parametric Saturation Approach in Phase Modulation Systems *

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Nonlinear phase noise (NLPN) is investigated theoretically and numerically to be mitigated by parametric saturation approach in DPSK systems. The nonlinear propagation equation that incorporates the phase of linear and nonlinear is analyzed with parametric saturation processing (PSP). The NLPN is picked and monitored with the power change factors in the DPSK system. This process can be realized by an optical PSP limiter and a novel apparatus with feedback MZI. The monitor range of phase noise is 0°–90°, which may be reduced to 0°–45° if the monitor factor is about the Stockes wave but not an anti-Stockes wave. It is shown that DPSK signal performance can be improved based on the parametric saturation approach.

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Differential-phase-shift keying (DPSK) signal has attracted much research attention. Compared with conventional on-off keying systems, DPSK systems possess many advantages such as higher receiver sensitivity, increasing spectral efficiency and an enhanced tolerance against fiber nonlinearity.[1] However, the phase noise is the main factor impacting the performance of DPSK system. Amplitude fluctuation caused by amplified spontaneous emission (ASE) noise is converted into phase noise by the Gordon–Mollenauer effect, which causes serious limitation to the system capacity in modern optical communications.[2] How to reduce the phase noise efficiently, especially the nonlinear phase noise (NLPN), becomes the essential steps to improve the performance of the phase modulation systems.

Researchers have used phase sensitive amplifiers to suppress the phase noise.[3,4] However, this approach, which needs a pump associated with the signal, is difficult to control the phase conjugation in a real system. In-line filters can be used to reduce phase jitters efficiently and to stablize the pulse power fluctuation,[5,6] whereas they could not reduce the noise jitters inside the signal bandwidth. The NLPN in a DPSK system can also be compensated for by nonlinear phase-shift compensators.[7,8] These apparatuses are similar to the regenerators of re-shaping pulse and poor in real-time with a complex structure.

Parametric-gain method has been modeled as interaction between the signal and the received ASE noise in PSK systems.[9] This parametric-gain processing may greatly affect the phase of carrier wave[10] and is an effective way to suppress the NLPN in femtosecond optical communication systems.[11] Utilizing characteristics of the parametric saturation processing (PSP) in a highly nonlinear fiber (HNLF), the amplitude fluctuations of signals are stabilized without disturbing signal phase. Unfortunately, these works only have a very coarse range in controlling of pump power to cut the over-shoot signal power. In this study, the parametric-gain processing is used to monitor and evaluate the NLPN of a DPSK system and a novel feedback module with a Mach–Zehnder interferometer (MZI) is designed to control the NLPN exactly. It can mitigate the NLPN of inside-band quickly and efficiently.

The origin of parametric processes lies in the nonlinear response of bound electrons of a medium material to an applied optical field. The second-order susceptibility $\chi^{(2)}$ vanishes for an isotropic medium in the dipole approximation like optical silicon fibers. The parametric process is third-order approximation depending on the third-order susceptibility $\chi^{(3)}$ and two photons at frequencies ω_1 and ω_2 are annihilated with a simultaneous creation of two photons at frequencies ω_3 and ω_4 under the phase-matching condition.[12] A strong pump wave at ω_2 creates two sidebands located symmetrically at frequencies ω_3 and ω_4, which are referred to the Stokes and anti-Stokes bands, respectively. The unsaturated gain can be given by an exact solution $G_0 = 1+\frac{16}{7}\sinh^2(\frac{\sqrt{7}}{4}\gamma P_P L)$ in neglecting any fiber losses in HNLF.[13] The saturation gain of signal can be $G = G_0/(1 + P_s/P_{\rm sat})$. Here L and γ are the length and the Kerr effect of HNLF. P_P, P_s and $P_{\rm sat}$ are powers of pump, signal and saturation of signal, respectively. We assume that a DPSK complex envelop in an N-channel WDM system can be expressed as

$$U(z,t) = \sum_1^N U_k(z,t)\exp(-j\omega_k t), \qquad (1)$$

where z is transmission distance, $k = 1, 2, 3, \cdots, N$,

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$U_k(z,t)$ is the signal complex envelope of the κ-th channel around ω_k. The evolution of $U(z,t)$ can be described by the nonlinear Schrodinger equation[12]

$$\begin{aligned}&\partial U_k(z,t)/\partial z\\ =&-\alpha U_k(z,t)-j\frac{1}{2}\beta_2\Big(-\omega_k+\frac{\partial^2}{\partial t^2}-j2\omega_k\frac{\partial}{\partial t}\Big)U_k(z,t)\\ &+\frac{1}{6}\beta_3\Big(\frac{\partial^3}{\partial t^3}-3j\omega_k\frac{\partial^2}{\partial t^2}-3\omega_k^2\frac{\partial}{\partial t}+j\omega_k^3\Big)U_k(z,t)\\ &+j\gamma\Big[\sum_{i=1}^{N}c_i|U_i(z,t)|^2U_k(z,t)\Big],\end{aligned}\tag{2}$$

where β_2 and β_3 represent the dispersion profile of second and third orders; α is the fiber loss; $c_i=1$ if $i=k$, otherwise$c_i=2$. Here we suppose that the frequency spectra in deferent channels have no overlapping and the signal is band limited. Then the linear phase shift $\phi_{Lk}(z)$ experienced by the carrier at ω_k due to chromatic dispersion and the nonlinear phase shift $\phi_{NLk}(z)$ due to SPM and XPM are

$$\phi_{Lk}(z)=\Big(\frac{1}{2}\beta_2\omega_k^2+\frac{1}{6}\beta_3\omega_k^3\Big)z,\tag{3}$$

$$\phi_{NLk}(z)=\gamma\left[\sum_{i=1}^{N}c_iP_i\right]\int_0^z\exp(-\alpha\xi)d\xi.\tag{4}$$

After the transmission through the fiber with the distance z, the linear phase shift can be compensated by the dispersion managed scheme.[14] The phase shift in channels 1 and 2 can be $\Delta\phi=(\phi_{01}-\phi_{02})+(\phi_{\rm NL1}-\phi_{\rm NL2})$, where $\phi_{01}-\phi_{02}$ is the difference between the original signal phases, and $\Delta\phi_{\rm NL}=(\phi_{\rm NL1}-\phi_{\rm NL2})$ is the difference between the nonlinear phase shifts of channels 1 and 2. If we control the pulse amplitude carefully in restraining the effect of XPM, the nonlinear phase shift may be cut down to very low level. In HNLF, this can be realized by the PSP. The signal phase with NLPN at ω_1 then can be represented as $\phi_1+\Delta\phi$. After it is combined with a pump light at ω_2 and then fed into a piece of HNLF, the two converted products are generated at $\omega_3=2\omega_1-\omega_2$ and $\omega_4=2\omega_2-\omega_1$. The light field of Stokes wave and anti-Stokes wave can be expressed as

$$\begin{aligned}E_{112}=&kE_1^2E_2\exp\{j[(2\omega_1-\omega_2)t\\ &+(2\phi_1+2\Delta\phi-\phi_2)]\},\end{aligned}\tag{5}$$
$$\begin{aligned}E_{221}=&kE_2^2E_1\exp\{j[(2\omega_2-\omega_1)t\\ &+(2\phi_2-\phi_1-\Delta\phi)]\},\end{aligned}\tag{6}$$

where ω_i, ϕ_i, $k(i=1,2)$ represent the angular frequency, the phase carried in the DPSK and CW light, and the efficiency of the PSP, respectively. Because the phases of the PSP products satisfy the relations $\phi_3=2(\phi_1+\Delta\phi)-\phi_2$ and $\phi_4=2\phi_2-(\phi_1+\Delta\phi)$, Stokes wave and anti-Stokes wave will be extracted by a band-pass filter after the HNLF. Here $\Delta\phi$ can be monitored and changed into an amplitude value where the phase modulations is transformed into amplitude modulations by the MZI. The variation of amplitude is proportional to the phase noise after a MZI and a photodiode. If anti-Stokes waves are monitored, the power change factor will be

$$K_1=\left|\frac{1+\exp(j\Delta\phi)}{2}\right|^2.\tag{7}$$

However, to Stokes wave, the power change factor will be

$$K_2=\left|\frac{1+\exp(j2\Delta\phi)}{2}\right|^2.\tag{8}$$

The monitor range of phase noise is 0°–90° in K_1, while the monitor range of phase noise will be cut to 0°–45° in K_2. From Eq. (4), it can be seen that the different nonlinear phase shifts are directly proporational to the pulse power, which may be effected by ASE noise. Numerical computing indicates that the signal power can be stabilized at certain level. As shown in Fig. 1, the signal power is stablized when the pump power is fixed. Here $\gamma=12\,({\rm w/km})^{-1}$, $L=1.6$ km. The saturated gain of signal is about 0.8 dB when pump power is varied from 40 mW to 45 mW. The signal power is stable at more and less around 13 mW.

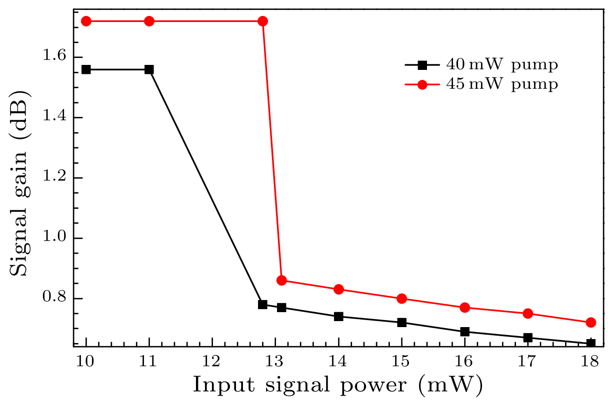

Fig. 1. Signal gain versus the signal power of PSP in HNLF.

A PSP limiter and monitor scheme in the DPSK system can be seen in Fig. 2. The optical signal combined with a pump is launched into the HNLF. When the signal power becomes comparable to the pump power, saturation of PSP takes place. Because the saturation is ultrafast and stable, it can be used as limiter to suppress bit-to-bit amplitude fluctuation of signal pulses. After the HNLF, we set a band-pass filter 2 to get rid of the rest pump power. At the same time, the filter 1 is set to monitor and estimate the phase noise and feedback to the receiver in electric signal. The simulation parameters of fibers are summarized in Table 1.

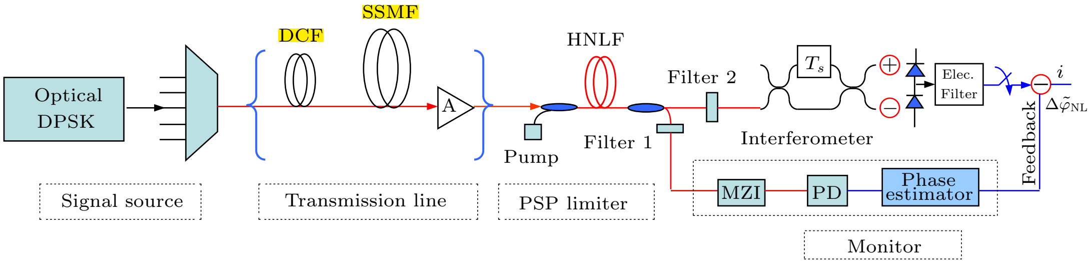

Fig. 2. PSP limiter and monitor scheme in the DPSK system.

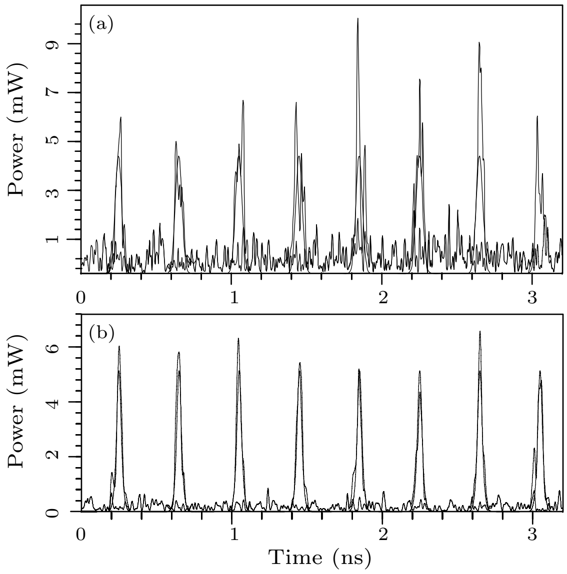

Fig. 3. Transmission optical pulse in the fiber with (a) and without (b) the PSP limiter.

Table 1. The parameters of fibers.

Parameters	DCF	SMF	HNLF
Length (km)	10	50	4.5
Dispersion slope (ps·km^{-1}·nm^{-2})	−0.3	0.075	0.026
Dispersion (ps·km^{-1}·nm^{-1})	−85	17	0.05
Effective core area (μm^2)	22	70	70
Loss (dB/km)	0.5	0.2	0.78

Other parameters of HNLF are, $\alpha = 0.78$ dB/km, $L = 4.5$ km. After the PSP limiter, differential phase shift $\Delta\phi_{NL}$ will be reduced to a small value. Figure 3 shows that with a PSP limiter in the fiber, amplitude fluctuations can be reduced. The signal power is varied about 5 mW to 10 mW without the limiter. However the output signal power ranges from 5 mW to 7 mW with the limiter and stabilized at about 6 mW. This process of reducing the pulse fluctuations is also found in Fig. 4 when the pump power is set differently at about 40 mW and 45 mW. Performance of the system is improved efficiently after PSP limiter. This can be seen in terms of Q-factor and eye-opening degradation with and without the PSP limiter in 10 Gbit/s and 40 Gbit/s DPSK systems in Fig. 5. It is shown that the signal noise ratio is improved almost 4 dB at 1800 km in the 10 Gb/s system. In the 40 Gb/s system, the 2 dB signal noise ratio gain can be received at 1800 km. Note that the degradation of eye-opening in different bit rates is mainly caused by the noise of inter-channels. The noise is resulted from either the contribution of nonlinear phase fluctuation caused by the intrachannel FWM in the transmission fiber or the ASE-induced phase noise during the transmission of modulated signals. The optimized dispersion map can be used to minimize the IXPM and IFWM effects in linear system and quasi-linear systems.[15,16]

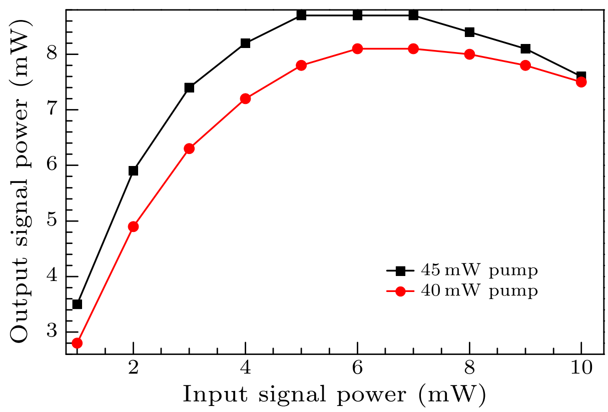

Fig. 4. Output signal power versus input signal power for different pump powers.

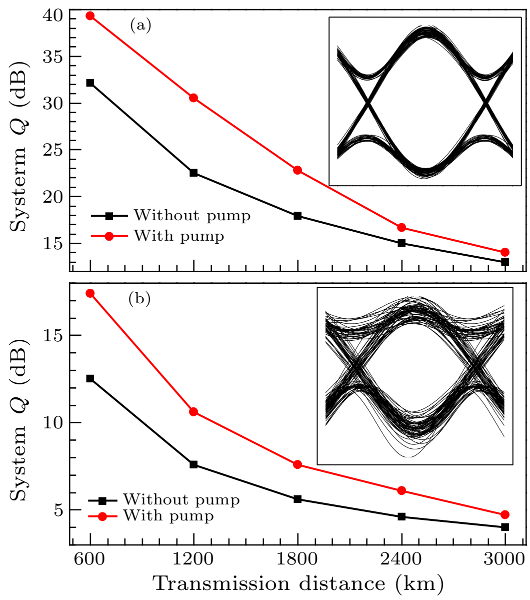

Fig. 5. System Q values versus transmission distance for different bit rates: (a) 10 Gbit/s, (b) 40 Gbit/s.

If we examine the anti-Stokes wave in the PSP with a Gaussian filter 1, a novel feedback module with a Mach–Zehnder interferometer (MZI) is designed to control the NLPN exactly in Fig. 2. The estimated value of phase $\Delta\tilde{\varphi}_{\rm NL}$ is feedback to the receiver. The factor of K_1 which is proportional to out/input power from the MZI is related to the estimated value of phase $\Delta\tilde{\varphi}_{\rm NL}$ in units of degree. Figure 6 show the relation of phase of NLPN in units of degree with K_1 when we monitor the anti-Stokes wave. The monitor range is from 0° to 90° corresponding to K_1 varying from 1 to 0.5. We also show the results of simulation with a commercial software package by an OptiWaves System 7.0. This shows good agreement with the results of our theory.

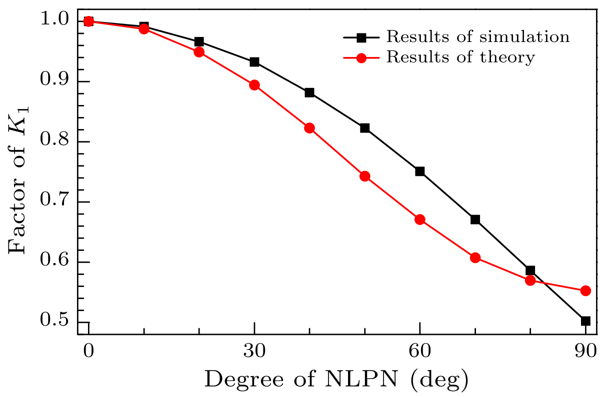

Fig. 6. Relationship of the phase of NLPN in units of degree with the factor K_1 in monitoring the anti-Stokes wave.

The further simulation shows that the results of suppressing NLPN after feeding the estimated phase back to the receiver are similar to Fig. 5, but the Q value has obtained about 2 dB gain. When white Gaussian noise with infinite bandwidth is assumed, the noise power approaches infinity. A finite signal-to-noise ratio requires some types of optical matched filters and does not distort the signal. With a very narrowband filter as in the model of Ref. [17], the nonlinear phase noise is independent of chromatic dispersion. The variance of nonlinear phase noise decreases with the increase of optical filter bandwidth. The optical matched filter may design on basis of signal structure and too complicated in optical domain. However, too wide bandwidth filter case corresponds to an almost unfiltered system. The different filter may also affect the Q value from the 17.4 dB to 19.6 dB when we use the filter in 10 Gbit/s. Then the filters essentially act by stabilizing the power fluctuations of the pulses, therefore reduce the nonlinear of the phase noise mediated by SPM.

In summary, we have discussed the PSP approach to restrain the phase noise of DPSK, and studied a real-time monitoring and suppressed the phase noise of a DPSK system. By using the PSP method, amplitude limiter suppresses the amplitude noise that is the origin of the NLPN. The Q value has an increase of 4 dB in the 10 Gbit/s system and 2 dB in the 40 Gbit/s system at a distance of 1800 km. The monitor range of phase noise is 0°–90° corresponding to the factor K_1 varying from 1 to 0.5, which may be reduced to 0°–45° if the monitor factor is about the Stokes wave. It is effective to improve transmission performance of DPSK signal by reduction of the NLPN. The future work will be focus on applying the PSP monitor to other high-spectral efficiency patterns such as in DQPSK systems.

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