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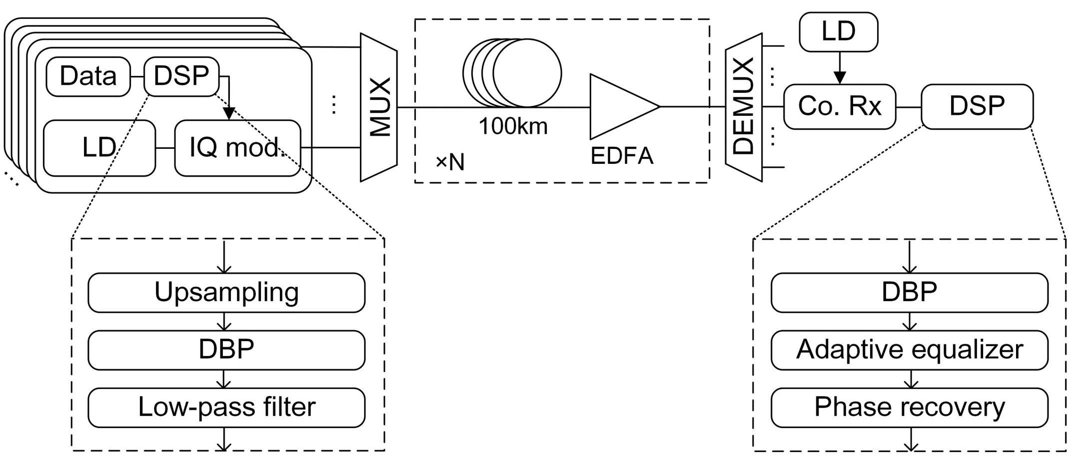

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XPM Mitigation in WDM Systems Using Split Nonlinearity Compensation

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Abstract: We propose a simple method to mitigate the cross phase modulation (XPM) effect in wavelength division multiplexing (WDM) systems, which combines the split nonlinearity compensation (NLC) and the receiver-side phase recovery algorithm. In the proposed method, the split NLC can suppress the conversion from the nonlinear phase noise (NLPN) to the Gaussian-like nonlinear interference noise (NLIN), and together with the phase recovery algorithm, which can compensate for the NLPN, the impact of the XPM on the signal is finally mitigated. This method is demonstrated by a transmission simulation with 11 WDM channels and 32 Gbaud 16 QAM modulations. The simulation results show that, due to the XPM mitigation, the proposed method can provide 0.4 dB gain for 500-km transmission, 0.3 dB gain for 2000-km transmission, and about 0.2 dB gain for 3000-km to 10000-km transmissions. The influence of the transmission distance on the gain is also discussed. Moreover, the selection of the phase recovery algorithm for different transmission distances is investigated, and the results show that for a short distance the blind phase search (BPS) is better, but for a long distance the V&V algorithm is more appropriate.

Index Terms: Cross-phase modulation, fiber nonlinearity compensation, split nonlinearity compensation, wavelength division multiplexing.

1. Introduction

Fiber nonlinearity is a critical issue that limits the capacity of the optical communication systems, especially the wavelength division multiplexing (WDM) systems [1], [2]. For intra-channel fiber nonlinearity, there have been lots of methods to compensate for it, either optical or digital, and the most famous one of them is the digital back-propagation (DBP) algorithm [1], [2]. Ignoring the computational complexity, DBP has the best performance among digital intra-channel nonlinearity compensation (NLC) methods and is often used as a reference for other NLC methods. Up to now, by applying the split NLC method, DBP can effectively compensate for the self-phase modulation (SPM) and mitigate the nonlinear signal-noise interaction [3], [4]. For inter-channel nonlinearity, however, the compensation is more complicated than the single-channel case.

At the beginning of this century, there were a lot of studies about the cross phase modulation (XPM) mitigation in WDM systems by optimizing the dispersion map of the system [5], [6]. This method increases the walk-off between the co-propagating channels and can effectively mitigate the XPM effects, but it is not suitable for the nowaday ultra-high-speed optical communication systems, which are usually coherent systems and dispersion un-managed [7]. For coherent optical communication systems, there are two kinds of methods to mitigate or compensated for the inter-channel fiber nonlinearity, optical or digital. For optical methods, optical phase conjugation is an effective method that can simultaneously compensate for the intra- and inter-channel fiber nonlinearity [8], [9]. Another optical method is the optical parameter amplifier, which can mitigate the nonlinear phase noise in WDM systems by the phase-sensitive characteristic [10]. However, in such optical methods, extra optical equipment is needed and the system configuration needs to be specially designed. For digital methods, multi-channel DBP is surely an effective method, but the requirement of the information of other receiving channels and the exponential computational complexity make it hard to implement in practical systems [11], [12]. Another approach is the subcarrier multiplexing, which can mitigate the XPM effects in WDM systems by subcarrier optimization [13], [14], but the implementation of this method depends on the modulation formats and it is also not suitable for the incoming dynamic optical network [1], 7]. Recently, Ronen Dar *et al.* proposed that the inter-channel fiber nonlinearity can be compensated by the adaptive equalizer [15], and Ori Golani *et al.* developed this idea and proposed to using the Kalman-MLSE equalization to mitigate the nonlinear interference noise (NLIN) [16]–[18], but the computational complexity is still high.

In this paper, we find that the single-channel split NLC method also has the property of XPM mitigation. By reducing the interaction between the XPM and the dispersion, the split NLC can mitigate the phase variation caused by XPM converting to the Gaussian-like NLIN. Combined with the phase recovery algorithm at the receiver, which can compensate for the nonlinear phase noise (NLPN), the XPM effect is finally mitigated. Compared with other XPM mitigation or compensation methods mentioned above, the proposed method does not need extra optical equipment and suits for different system configurations and modulation formats. And because the used algorithms are simple and the information of other channels is not required, the proposed method has low computational complexity. Actually, the utilization of the split NLC method in WDM systems has been studied in [19]. However, the authors adopted the Gaussian noise (GN) model but not transmission simulation in their studies, and because of the limitation of the GN model, they did not find the XPM mitigation ability of the split NLC method in WDM systems. In this paper, the XPM mitigation effectiveness of the split NLC method in WDM systems is demonstrated by a transmission simulation with 11 channels and 32 Gbaud 16 QAM modulations. The relationship between the gain and the transmission distance and the selection of the phase recovery method are also discussed.

2. Principle

In WDM systems, if ignore the dispersion, the XPM effect of the interfering channels only brings phase variation to the interested channel. For a WDM system with many channels, according to the central limit theorem, the phase variation caused by the XPM of the interfering channels is closed to a Gaussian random process. For the interested channel, when considering the dispersion, the phase variation interacts with the dispersion along the fiber transmission, and are converted into the intensity fluctuations. When the accumulated dispersion is large enough, the NLIN has similar characteristics as the GN, which is the fundament of the GN nonlinearity model [20]. When the accumulated dispersion is not so large, the phase variation caused by the XPM will not be all converted into the Gaussian-like NLIN, and the residue of the phase variation makes up a part of the NLPN. Since the conversion of the phase variation to the Gaussian-like NLIN is a distributed process along the fiber, by reducing the interaction length of the XPM phase variation and the dispersion, the Gaussian-like NLIN can be mitigated, but the NLPN in the system will increase. Fortunately, the NLPN can be partly compensated by the phase recovery algorithm. So, finding a method that can reduce the interaction between XPM phase variation and dispersion, together with the receiver-side phase recovery algorithm, it is feasible to mitigate the impact of the XPM in WDM systems.

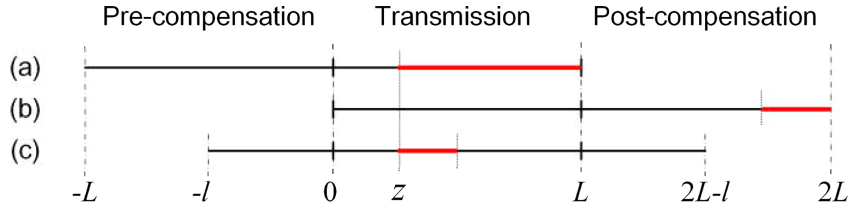

Fig. 1. The interaction lengths between the XPM and the dispersion of the three dispersion compensation schemes: (a) dispersion pre-compensation, (b) dispersion post-compensation and (c) split dispersion compensation.

From our previous study in [4], the nonlinear signal-noise interaction is also a distributed process along the fiber, and the NLC method reduces the interaction length of the noise and the SPM and effectively mitigates the nonlinear signal-noise interaction. With the same idea, the split dispersion compensation can also reduce the interaction length of the dispersion and the phase variation caused by XPM. Fig. 1 displays three different dispersion schemes, including dispersion pre-compensation, dispersion post-compensation and split dispersion compensation. Assume that the transmission distance is L, and the pre-compensation length of split dispersion compensation is l. Considering that the phase variation caused by XPM is "added" into the interested channel at the point z, it will interact with the dispersion of the rest of the fiber link and the dispersion post-compensation. It should be noted that the dispersion of the fiber link and the post-compensation is opposite and they will cancel out each other. Taking the case (b) in Fig. 1 as an example, the XPM phase variation at point z will interact with the dispersion of fiber link with length $L - z$ and the dispersion post-compensation with length L. But the dispersion post-compensation with length $L - z$ will cancel out the dispersion of the fiber link with length $L - z$, and finally, only the dispersion of the post-compensation with length z will interact with the XPM, which is identified as the red line in Fig. 1. The other two cases can be analyzed in the same way, and the accumulated interactional dispersion of the three compensation schemes can be calculated by integrating the point z in the whole transmission link:

$$D_{pre} = \int_0^L \beta_2 (L - z) dz = \beta_2 L^2/2, \tag{1}$$

$$D_{post} = \int_0^L \beta_2 z dz = \beta_2 L^2/2, \tag{2}$$

$$D_{split} = \int_0^l \beta_2 (l - z) dz + \int_l^L \beta_2 (z - l) dz = \beta_2 (l^2 - lL + L^2/2), \tag{3}$$

where β_2 is the dispersion parameter of the fiber, and the subscript "pre", "post" and "split" are corresponding to the three compensation schemes. It is obvious that the split dispersion compensation scheme has the smallest accumulated interactional dispersion. Though in the analysis above the power distribution along the distance is neglected, for a long-reach multi-span system, we can treat each span as a whole and the fiber nonlinearity of each span is uniformly distributed in the transmission link, and the analysis is still effective.

After including the intra-channel fiber nonlinearity compensation, the split dispersion compensation evolves into the split NLC. That is, the split NLC not only can compensate for the intra-channel fiber nonlinearity, but also has the ability to mitigate the XPM effect combined with the phase recovery algorithm in WDM systems.

3. Simulation Setup

A transmission simulation with 1 interested channel and 10 interfering channel is performed. The simulation setup is illustrated in Fig. 2. At the transmitter, the lasers with different wavelengths and

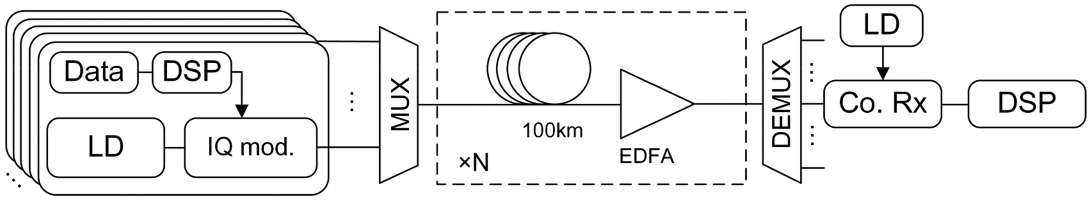

Fig. 2. Simulation setup: LD- laser diode; IQ mod- IQ modulator; Co. Rx- coherent receiver.

the same linewidth of 100 kHz are used as the resources and then modulated with different 16 QAM signals. The channel space is 100 GHz, and the modulation rate is 32 Gbaud. The central wavelength of the interested channel is 1550.12 nm, and there are 5 interfering channels on both sides of the interested channel, respectively. In the simulation, to exclude the impact of the dispersion of the interfering channels on the interest channel, the 10 interfering channels are not processed with any digital signal processing (DSP) algorithm at the transmitter. The fiber transmission is simulated by numerically solving the coupled nonlinear Schrödinger equations with 8 sample/symbol. The polarization effect is ignored in the transmission. The transmission link contains 100 spans, and each span has a 100-km standard single mode fiber and an EDFA. The EDFA in each span exactly compensates for the span loss, and the noise figure is 5 dB. After coherent detection, the signal was processed by a chain of DSP algorithms. In the simulation, the receiver-side NLC and the split NLC are applied for comparison, and they are realized by the DBP algorithm. To avoid the impact of the upsampling and downsampling operation, both the transmitter-side DBP and the receiver-side DBP are operated with 8 sample/symbol. After receiver-side DBP, the signal is processed by an adaptive equalizer with the multi-modulus algorithm, and then the phase recovery is applied to compensate for the laser phase noise and the NLPN. In the simulation, we use two kinds of phase recovery algorithms, one is the traditional two-stage Viterbi and Viterbi (V&V) algorithm, and the other one is the low-complexity blind phase search (BPS) algorithm [21]. Finally, the SNR of the signal is calculated as the output.

4. Results and Discussion

4.1 XPM Mitigation Performance

To demonstrate the split NLC scheme has the ability of XPM mitigation, we first do a 2000-km transmission simulation. Considering that the split NLC has gain in the single-channel condition due to the nonlinear signal-noise interaction mitigation, a single-channel simulation is carried out for comparison. The final signal SNRs of both single-channel and multi-channel case with different NLC schemes are shown in Fig. 3. From Fig. 3(a), it can be seen that in the single-channel case, the split NLC has about 1.3 dB SNR gain over the receiver-side NLC, and the gain comes out when the signal power exceeds 3 dBm. For the multi-channel case, because of the inter-channel fiber nonlinearity, the optimal incident power of each channel is much lower than the single-channel case. As we can find in Fig. 3(b), which shows the simulation results of the multi-channel case, the optimal incident power per channel is 1 dBm. From Fig. 3(a), when the incident power is 1 dBm, because of the low incident power, the nonlinear signal-noise interaction in this system is negligible, and the split NLC brings almost no gain to the signal over the receiver-side NLC. Therefore, we can exclude that the gain brought by the split NLC in the multi-channel case is due to the nonlinear signal-noise interaction mitigation. From Fig. 3(b), it can be seen that the split NLC scheme has about 0.3 dB improvement over the receiver-side NLC scheme, and all the gain comes from the XPM mitigation.

Fig. 4 displays the final signal SNRs with different transmission distances varying from 500 km to 10000 km. From Fig. 4, we can find that for all transmission distances, the split NLC scheme has better performance than the receiver-side NLC scheme. The relationship between the gain and the transmission distance will be discussed in Section 4.3.

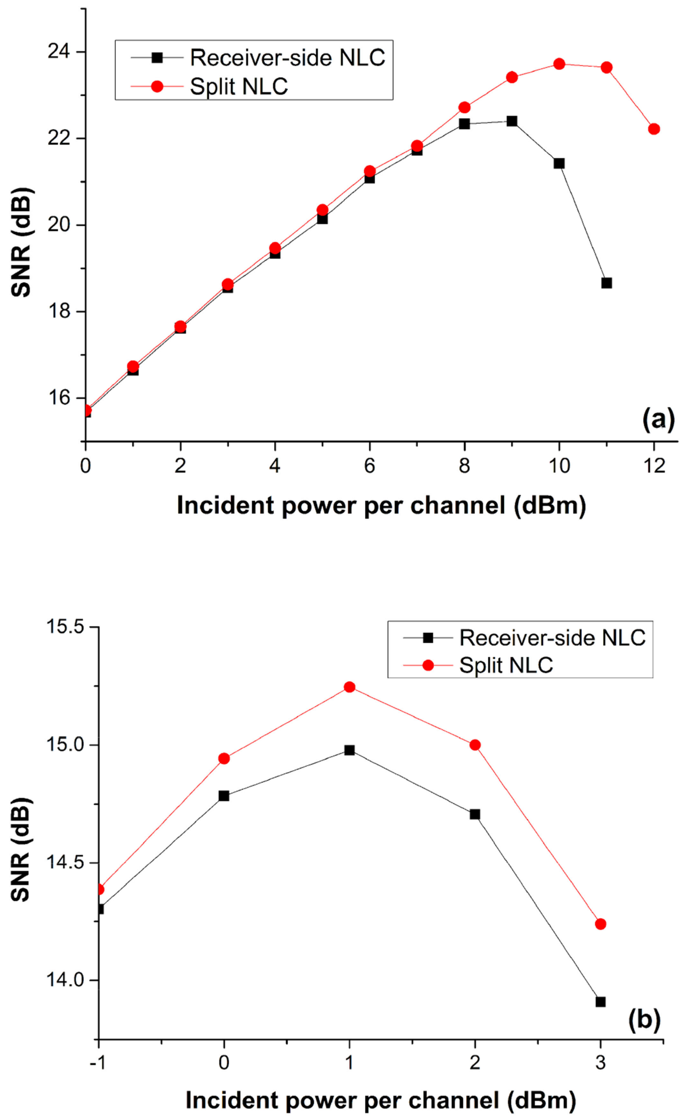

Fig. 3. The final signal SNRs with different NLC schemes: (a) the single-channel case and (b) the multi-channel case.

It should be noted that, in Fig. 3 and Fig. 4, the gains provided by the split NLC method are on the basis of BPS algorithm, and the BPS algorithm has about 0.3-0.5 dB SNR gain over the case without any XPM mitigation methods when the transmission distance is not long enough (about less than 3000 km) [22]. So compared with the case without any XPM mitigation, the proposed method in this paper can provide about 0.7-0.9 dB SNR gain in the 5×100 km transmission, which is closed to the adaptive equalizer method in [16]. Moreover, thanks to the low-complexity BPS algorithm form the previous work of our team in [21], the computational complexity of the proposed method is much lower than the adaptive equalizer.

4.2 Pre-Compensation Length

When the split NLC is applied in the single-channel system for nonlinear signal-noise interaction mitigation, the performance of the split NLC is related to the pre-compensation length, and the

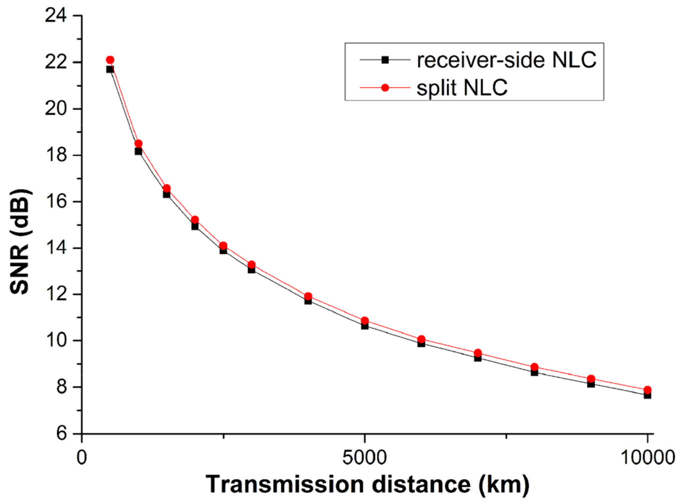

Fig. 4. Comparison of different compensation schemes with different transmission lengths.

optimal split ratio is 50%. Similar to the single-channel case, the utilization of split NLC in the multi-channel system also has an optimal split ratio, and on the existing experience, the optimal split ratio should also be 50%. According to the analysis in Section 2, the conversion of the XPM phase variation to the Gaussian-like NLIN is related to the accumulated chromatic dispersion. Though the conversion relationship is not linear, by calculating the total accumulated chromatic dispersion which interacts with the XPM phase variation, the optimal split ratio is corresponding to the minimum point of the accumulated chromatic dispersion. By calculating the derivative of D_{split} in (3), it can be found that the minimum point appears when the pre-compensation length $l = L/2$, which is corresponding to the 50% split ratio.

Fig. 5 displays the SNR gain of the split NLC varying with the split ratio in the simulation, and the different curves are corresponding to different transmission distances. Though there are some fluctuations due to the noise, it can be seen that the optimal split ratios for all the transmission distances are all about 50%, which agrees with the analysis result above.

4.3 Transmission Distance

In this sub-section, the impact of the transmission distance on the gain of the split NLC is discussed. Fig. 6 displays the relationship between the gain of the split NLC and the transmission distance. In Fig. 6, there are two cases: the black square markers are the normal transmission case, and the red triangular markers are the case of transmission with no ASE noise, which is for comparison. From Fig. 6, it can be found that both for the normal case and the noiseless case, the gains of the split NLC have a similar trend, which decreases first and then keep a relatively stable value with the increase of the transmission distance. For the normal transmission case, the SNR gain is about 0.4 dB when the distance is 500 km, and the gain decreases to about 0.2 dB when the distance is about 3000 km. For longer transmission distance from 3000 km to 10000 km, the gain keeps about 0.2 dB. Compared with the normal transmission case, in the noiseless transmission case, the gain brought by the split NLC is much higher and decreases slower.

In the analysis in Section 2, the gain brought by the split NLC method origins from two parts: one is the Gaussian-like NLIN mitigation caused by the reduction of the interaction of the XPM phase variation and the chromatic dispersion, and the other is the compensation of the NLPN by the phase estimation algorithm. With the increase of the transmission distance, the two parts above will be affected and the final gain changes.

The first issue that has an influence on the gain is the final signal SNR, which will impact the optimal block length of the phase estimation algorithm. For high SNR, the noise is small,

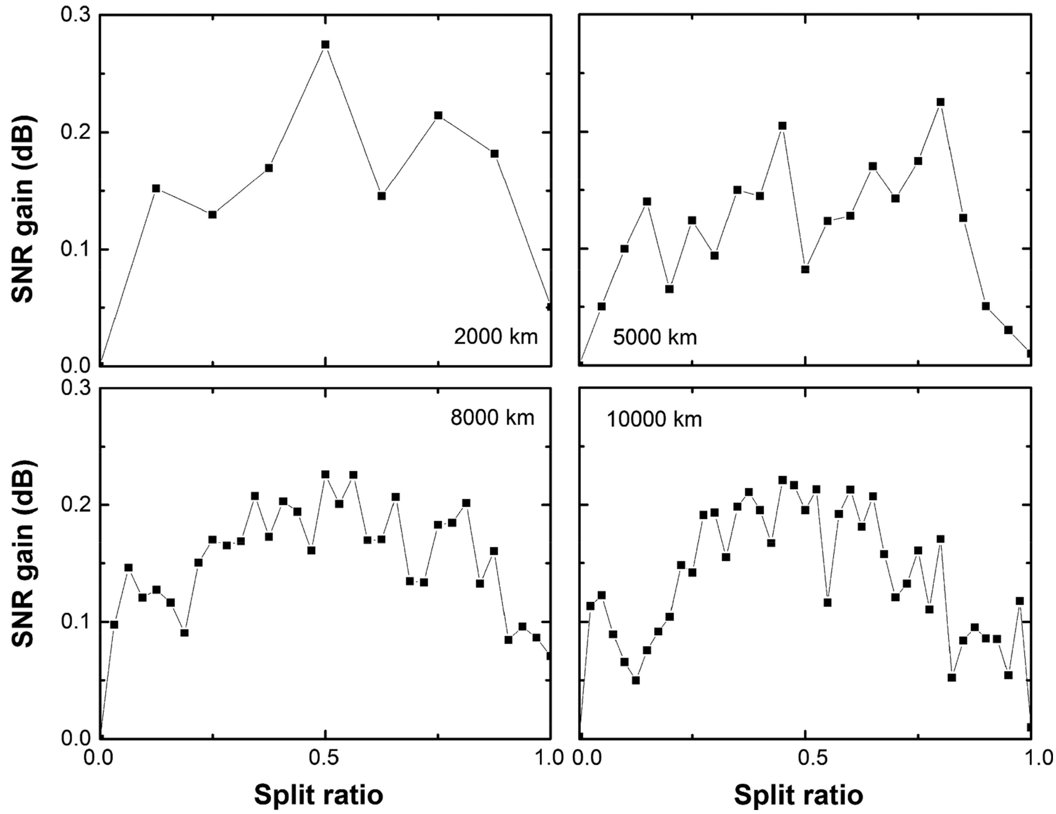

Fig. 5. The relationship of the SNR gain of split NLC and the split ratio, with different transmission distances.

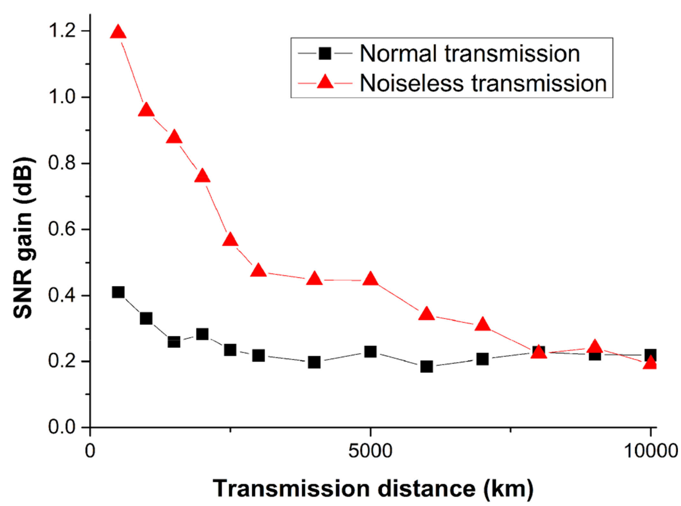

Fig. 6. The gain of the split NLC varies with the transmission distance.

and the optimal block length is also a relatively small value, which leads to good compensation for the NLPN. With the signal SNR decreases, the optimal block length of the phase estimation algorithm increases to suppress the ASE noise, which will degrade the performance of the NLPN compensation. This can be demonstrated by the comparison of the case of normal transmission and the case of noiseless transmission. When the transmission distances are the same, because

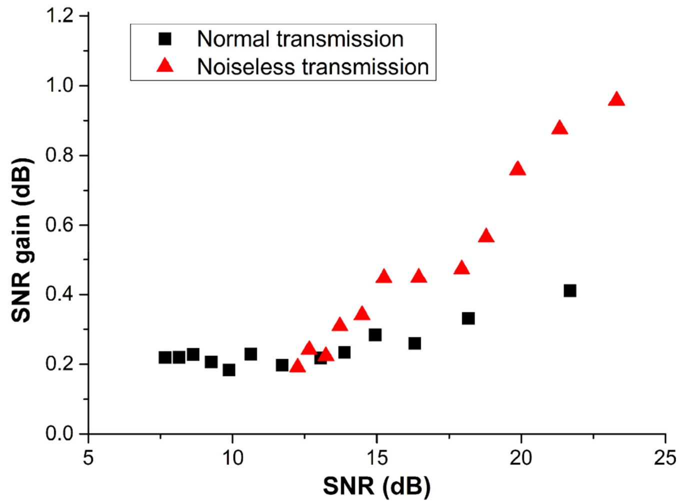

Fig. 7. The relationship between the gain and the signal SNR.

in the noiseless case the final signal SNR is higher than the normal case, the gain of split NLC is higher, too. However, when the SNR continues decreasing to a relatively small value, the block length of the phase estimation algorithm is long enough, and the gain of split NLC stops decreasing. This can explain the phenomenon that the gain keeps about 0.2 dB when the transmission distance is over 3000 km in the normal case. And for the noiseless case, the gain no longer decreases after about 8000 km. Fig. 7 displays the relationship between the gain and the final signal SNR. It can be seen that the threshold SNR is about 13 dB, and below the threshold, the gain of the split NLC will keep a relatively stable value.

From Fig. 7, by comparing the results of the two cases with the same SNR but different transmission distance, it can be found that the gains of the normal case and the noiseless case are still different. It means that besides the transmission distance impacts the final signal SNR, the transmission distance also has an influence on the gain of split NLC in other ways. On one hand, longer transmission distance means more accumulated fiber nonlinearity, and the gain of split NLC is higher. In Fig. 7, comparing the two cases with the same SNR but different distances, the gain of the noiseless case, which has longer transmission distance, is higher than the normal case. On the other hand, when the transmission distance increases, the accumulated dispersion also increases and the effect that the pre-compensation reduces the interaction between the dispersion and XPM is becoming weaker, which leads to the gain of the split NLC decreasing. So, in Fig. 7, with the transmission distance increasing (SNR decreasing), the difference between the gains of the two cases becomes smaller and smaller.

4.4 Selection of the Phase Estimation Method

In the proposed method, the pre-compensation reduces the interaction between the XPM and the dispersion, which makes the impact of the XPM on the signal more tends towards the phase noise. In this condition, the phase estimation method is a critical issue that should be investigated. In this sub-section, two popular phase estimation algorithms, including the two-stage V&V algorithm and the BPS algorithm, are applied in the receiver-side DSP, and the results are shown in Fig. 8.

In Fig. 8, there are three transmission distances, 2000 km, 5000 km and 10000 km. For each distance, two compensation schemes, the receiver-side NLC and split NLC, and two phase estimation algorithms mentioned above are applied. For 2000 km transmission, because the final signal SNR is relative high, the BPS algorithm has obvious advantage of accuracy over the V&V algorithm, and the performance of the BPS algorithm is better than the V&V algorithm. It can be

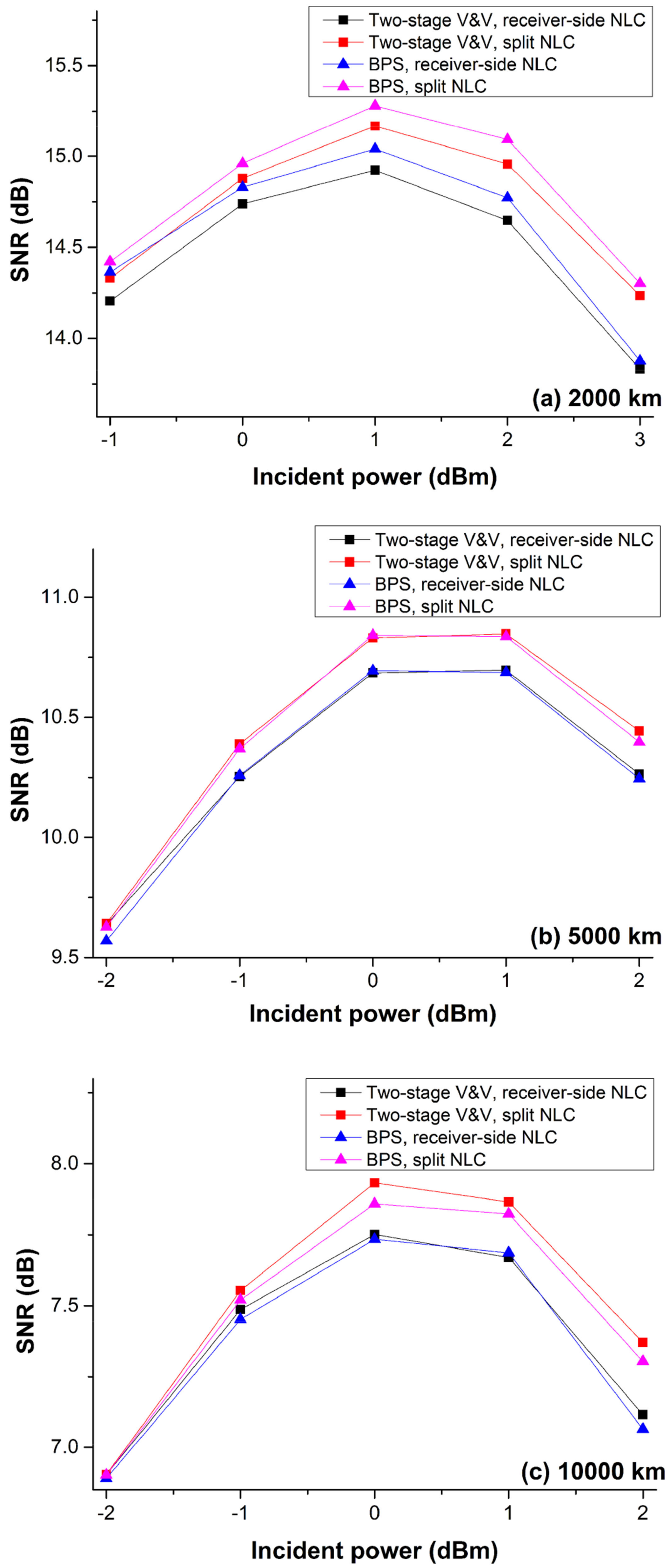

Fig. 8. The SNRs with different incident powers. (a) 2000 km, (b) 5000 km, and (c) 10000 km.

obviously seen from Fig. 8(a), the SNR of the case of BPS is about 0.15 dB higher than the case of V&V algorithm. With the increase of the transmission distance, the signal SNR decreases and the advantage of the noise mitigation of the V&V algorithm emerges, and the performances of the two phase estimation algorithms become close to each other. In Fig. 8(b), when the transmission distance is 5000 km, the BPS and the V&V have the same performance. Moreover, if the signal SNR is small enough, the noise mitigation ability of the phase estimation algorithm is critical, and in this condition the two-stage V&V algorithm is better than the BPS algorithm, which can be demonstrated by the results of the 10000-km transmission in Fig. 8(c). The results show that for a short distance the BPS is better, but for a long distance the V&V algorithm is more appropriate.

5. Conclusion

We find and demonstrate that the split NLC can be used in WDM systems to mitigate the XPM effect together with the receiver-side phase recovery algorithm. The mechanism of the XPM mitigation is the pre-compensated dispersion of the split NLC can reduce the interaction length between the XPM phase variation and the chromatic dispersion, which can suppress the conversion from the NLPN to the Gaussian-like NLIN. And combined with the receiver-side phase recovery algorithm, which can compensate for the NLPN, the XPM in the system is finally mitigated. Because the information of other channels is not needed and the used algorithms are simple, the proposed XPM mitigation method is simple and easily deployed. Though a transmission simulation with 11 channels, the results show that the proposed method can provide 0.4 dB gain for 500-km transmission, 0.3 dB gain for 2000-km transmission, and about 0.2 dB gain for 3000-km to 10000-km transmissions. For the practical implementation of this method, the optimal split ratio of the split NLC is 50%. And at the receiver, for a short distance the BPS is better, but for a long distance the V&V algorithm should be chosen.

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