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REVIEW ARTICLE

Multi-channel phase regeneration of QPSK signals based on phase sensitive amplification

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Abstract In this paper, we propose and demonstrate simultaneous phase regeneration of four different channels of QPSK signal based on phase sensitive amplification. The configuration can be divided into two parts. The first one uses four wave mixing in high nonlinear fiber (HNLF) to generate the corresponding three harmonic conjugates precisely at the frequency of the original signals. The other one uses optical combiner to realize coherent addition which is aimed at completely removing the interaction in phase regeneration stage. The simulation results suggest that this scheme can optimize signal constellation to a large extend especially in high noise environment. Besides, optical signal to noise ratio (OSNR) can improve more than 3 dB while the bit-error-rate (BER) reaches 10^{-3} with a constant white noise and 15° phase noise.

Keywords four wave mixing, multi-channel, coherent addition, phase sensitive regeneration, optical combiner

1 Introduction

Considering the potential of optical fiber communications to realize large capacity, long distance and more efficient spectrum, a variety of researches have been made in all optical signal processing [1,2] and network algorithm [3], especially in advanced modulation format signal for its high spectral efficiency [4,5]. However, in the transmission system, the accumulation of chromatic dispersion, loss and nonlinear effect is inevitable and will deteriorate the primary signal. So it is very necessary to implement phase regeneration especially for advanced modulation format signals which are more sensitive to noise.

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Phase sensitive amplifier (PSA) can deal with these challenges for its inherent characteristic to realize phase sensitive squeezing [6] and low noise amplification which can overcome the conventional quantum limit in theory [7] compared to those phase insensitive amplifier, such as erbium doped fiber amplifier (EDFA). In consideration of the rare advantages of PSA, there are already many researches on it to optimize the signal in a single channel, such as phase regeneration [8–10], phase quantization [11–13] and modulation format conversion [14–16]. However, allowing for the inevitable wavelength division multiplexing (WDM) transmission system, it is very significant for us to do more researches on simultaneously dealing with multi-channel signals. Seeing from the previous research results and our personal point of view, one of the most difficulties lying in phase regeneration of the WDM transmission system is the unnecessary interaction among signal, pump and harmonic in different channels.

Nowadays, there are already some researches on multi-channel signals. Sygletos et al. successfully realized the regeneration of two channel differential phase shift keying (DPSK) signals using “black box” construction in 2011 [17]. Later, in 2014, they achieved the regeneration of two channel quadrature phase shift keying (QPSK) signals with the same construction [18]. However, it can only deal with a few signals in different channel because it cannot effectively restrain the interaction between different channels. In 2015, Guan et al. used the optical Fourier transformation (OFT) construction which conversed multi-channel signals on frequency domain into one to realize the regeneration of four channel binary phase shift keying (BPSK) signals [19]. Parmigiani et al. achieved the regeneration of six channel BPSK signals with polarization assisted PSA (PA-PSA) construction in 2016 [20]. Although using polarization can effectively reduce the interaction among pump, signal and harmonic in different channels, it is difficult to control. At the same time, using polarization will lose a part of energy of our system. Besides these weakness, most of these researches focused on the BPSK signals, only a few dealing with the QPSK signals or more advanced modulation format signals.

In this paper, we propose and simulating demonstrate a novel configuration using bi-direction to simultaneously regenerate four different channels of QPSK signals based on phase sensitive amplification. In harmonic generation stage, we use four wave mixing in two-mode phase conjugate (PC) process to generate the necessary idlers located precisely at the frequency of corresponding original signals. It can help us to adjust the amplitude ratio between signal and harmonic to reach the optimal regeneration effect in the following phase regeneration stage. At the same time, we utilize common pump to achieve symmetrically reaction, avoiding the strong and undesired interaction between pump and pump. In phase regeneration stage, we use optical combiner instead of nonlinear medium to realize phase regeneration by coherent addition which can avoid undesired nonlinear interaction among signal, pump and harmonic. The simulation results suggest the improvement of signal constellations and bit-error-rate (BER) to a large extent.

The following content of this paper is organized as follows. Section 2 introduced the operation principle for regeneration of four different channels of QPSK signals. On the basis of the operation principle, Section 3 describe the simulation setup used in our regeneration system and we give the results analyzing in Section 4. At last, we conclude the total paper in Section 5.

2 Operation principle

There are two important processes in optical phase regeneration. The first one is the generation of the $-(M-1)$ harmonic and the other is the interference between the original signals and the $-(M-1)$ harmonic. When it comes to QPSK signal, the regeneration process can be given as follows

$$A_{out}*\exp(i\varphi_{out}) = A_{in}[\exp(i\varphi_{in}) + m*\exp(-3i\varphi_{in})], \quad (1)$$

where φ_{in} is the input phase while φ_{out} is the output phase. m is the amplitude ratio between signal and harmonic. In a constant noisy environment, different generation efforts come with the different amplitude ratio.

To avoid uncontrollable interaction among signal, pump and harmonic, we choose optical combiner instead of nonlinear medium to realize coherent addition. At the same time, it is more convenient for us to adjust the amplitude ratio between φ_{in} and $-3\varphi_{in}$ to reach the perfect regeneration effect. Taking S_1 and S_3 for example, the frequency and phase relationship in harmonic generation stage is described in Fig. 1.

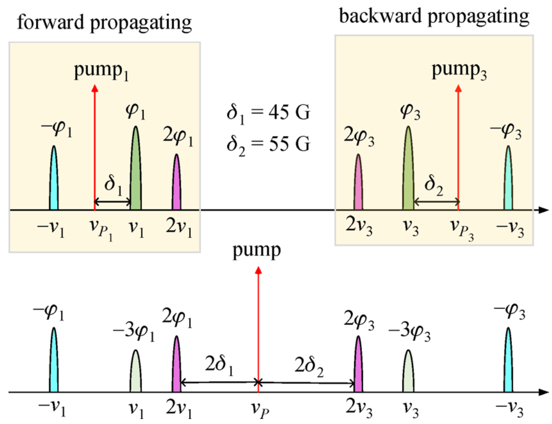

Fig. 1 Frequency and phase relationship

First, we launch S_1 and S_3 with their corresponding pump into the nonlinear medium to generate their corresponding conjugates as well as second harmonics by bi-direction. The frequency interval δ_1 between S_1 and pump$_1$ is 45 GHz while δ_2 between S_3 and pump$_3$ is 55 GHz. The frequency interval between S_1 and S_3 is 300 GHz which can make the fourth harmonic of S_1 and S_3 produced in the same location after cascade four wave mixing. Secondly, we select these conjugates and second harmonics and then combine the four waves with a common pump into another nonlinear medium. The common pump is located just at the fourth harmonic of both S_1 and S_3. In this nonlinear medium, we can use four wave mixing in two-mode PC process to simultaneous generate two new waves at the frequency of the original S_1 and S_3. Seeing from the four wave mixing respectively, the input waves include conjugates, second harmonics and the common pump. According to the phase relationship of four wave mixing, the phase of the new wave $\varphi = \varphi_P + (-\varphi_{in}) - 2\varphi_{in}$. Assuming the common pump does not carry the information of signal, φ_P can be treated as zero. It indicates that the new waves are exactly the high-order conjugates $-3\varphi_{in}$ of S_1 and S_3.

In the same way, we can generate the two high-order conjugates $-3\varphi_{in}$ at the frequency of the original S_2 and S_4. Finally, we can realize simultaneous phase regeneration of the four signals in the optical combiner by the coherent addition of original signals and high-order conjugates $-3\varphi_{in}$.

3 Simulation setup

To verify the operation principle mentioned above, we simulate the simultaneous phase regeneration of four different channels of QPSK signals. Figure 2 shows the simulated setup used in the multi-channel phase regeneration of QPSK signals.

The four continuous wave (CW) lasers (λ_1: 1553.599 nm,

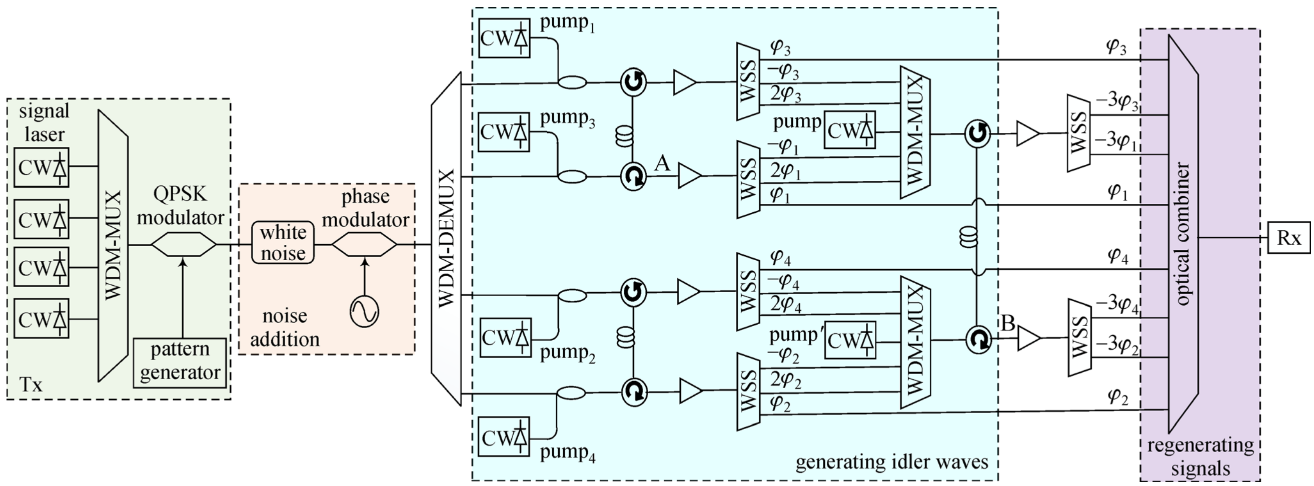

Fig. 2 Simulated setup for four different channels of QPSK signals. Tx: transmitter; Rx: receiver; WDM-MUX: wavelength division multiplexer; WDM-DEMUX: wavelength division demultiplexer; WSS: wavelength selective switch

λ_2: 1552.795 nm, λ_3: 1551.189 nm, λ_4: 1550.388 nm) are combined together and then fed into a serial-cascade-type of QPSK modulator which is driven by 10-Gbps pseudo-random binary sequences (PRBSs) to generate the QPSK signals. To make it closer to reality, $5\mathrm{e}^{-15}\ \mathrm{W \cdot Hz^{-1}}$ white noise and a phase modulator driven by a 1 GHz sine wave are used to emulate amplitude and phase noise in transmission. Afterwards, signals are divided and combined with their corresponding pump. Then S_1, P_1 and S_3, P_3 are launched into a 200 m bi-direction HNLF with zero-dispersion wavelength of 1553.599 nm, and nonlinear coefficient of 13.144 $(\mathrm{W \cdot km})^{-1}$. S_1 and P_1 are forward propagating while S_3 and P_3 are backward propagating. Then we select their corresponding conjugates and second harmonics and join with their common pump in another high nonlinear fiber (HNLF) to generate the two high-order conjugates $-3\varphi_{in}$. In the same way, we can obtain other two high-order conjugates $-3\varphi_{in}$ of S_2 and S_4. Finally, we launch the four high-order conjugates $-3\varphi_{in}$ and the four original signals filtered from the output of first four wave mixing process into optical combiner to realize phase regeneration by coherent addition. The power rate between high-order conjugates $-3\varphi_{in}$ and original signals is around 0.5 which can display a relatively superior regeneration effect. Figure 3 shows the frequency spectra at the points of A and B.

4 Results analyzing

Although our research focus on phase regeneration, we still add white noise into our configuration to emulate amplitude and phase noise because they are both inevitable in a real transmission system.

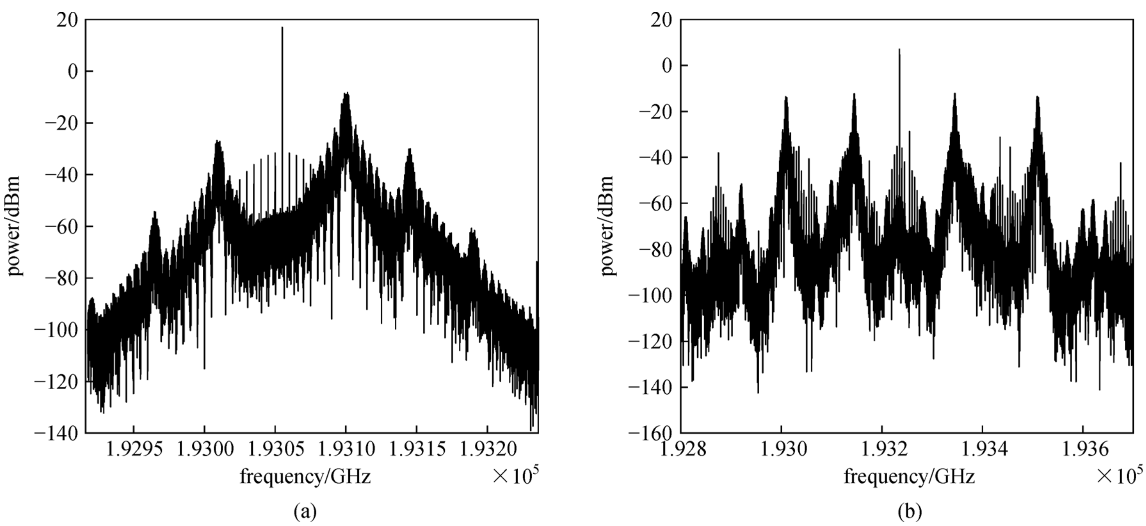

Fig. 3 Frequency spectra at the points of (a) A and (b) B

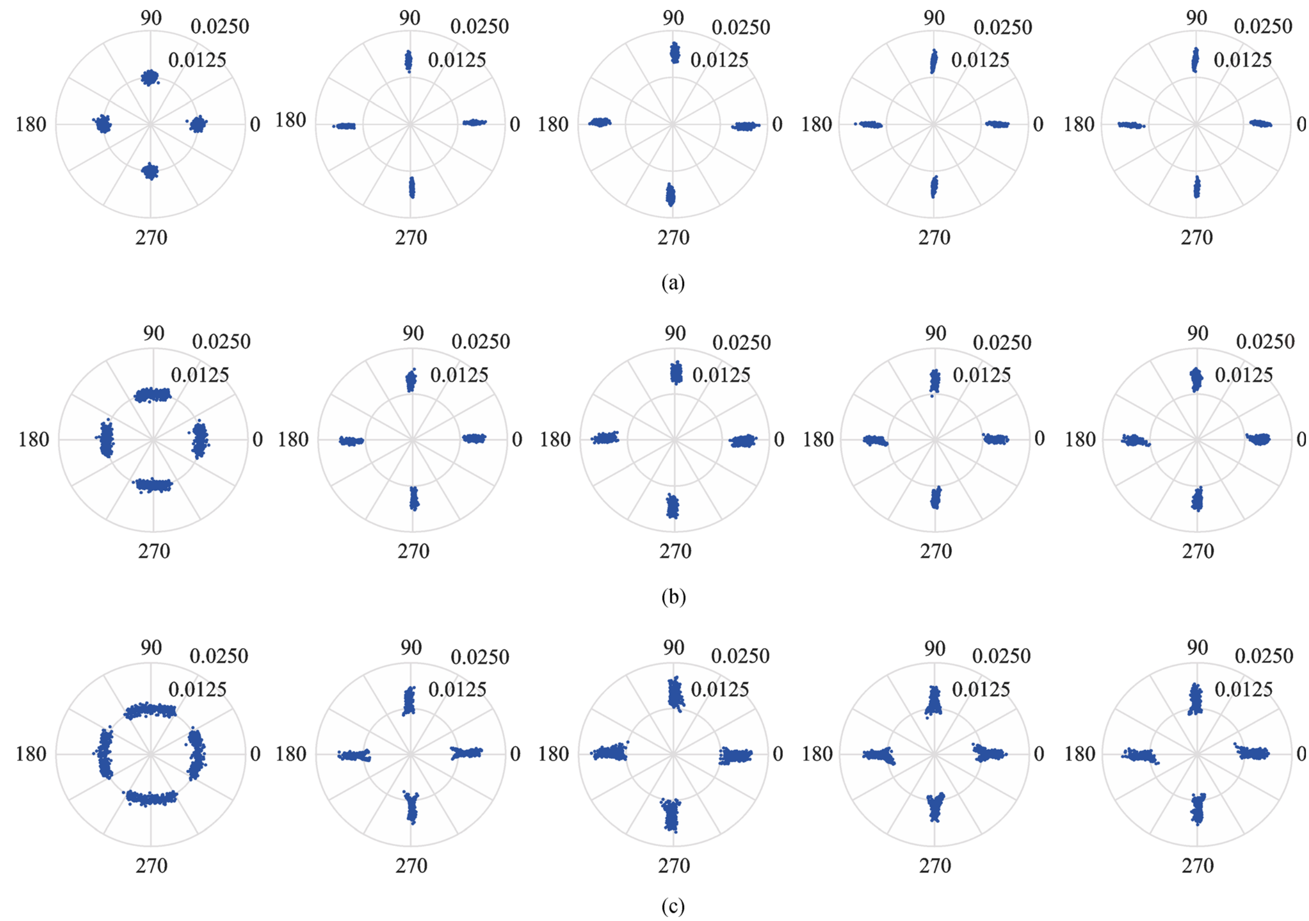

Fig. 4 Constellations of input and output signals (from left to right: input, output of S_1, S_2, S_3, S_4). (a) Only add white noise; (b) add white noise and 15° phase noise; (c) add white noise and 25° phase noise

Figure 4 shows the constellation of four channels while different noises are added into our configuration. Respectively seeing Figs. 4(a), 4(b) and 4(c), it can be observed that the constellation of different signal outputs are very similar and squeezed tremendously at QPSK's four symbols compared with the input constellation. In contrast, Figs. 4(a), 4(b) and 4(c) show the similar regeneration effect with different noises. Especially in Fig. 4(c), the input constellation is deteriorative sharply because of adding white noise and 25° phase noise while the four outputs are still very distinct after regeneration.

Seeing from the constellation before and after regeneration, it is obvious that amplitude noise is introduced while the phase noise can be squeezed. In fact, after regeneration, there is not new noise introduced, but convert the phase noise to amplitude noise. The configuration makes use of the inherent characteristic of PSA to realize phase sensitive squeezing. For phase modulated signals, after the regeneration of PSA, the in-phase components will be amplified while the quadrature components will be compressed. When it comes to QPSK, the signals and high-order conjugates $-3\varphi_{\text{in}}$ at the same frequency that satisfy the phase-matching relationship can interfere. Then 0, $\pi/2$, π, $3\pi/2$ phase points will be amplified while $\pi/4$, $3\pi/4$, $5\pi/4$, $7\pi/4$ phases points will be squeezed. Seeing from the noisy constellation, it manifests that phase noise converts into amplitude noise.

To further analysis, BER is measured in Fig. 5. The results suggest the similar regeneration effect by almost overlapping BER curves among four different channels. When the system BER reaches 10^{-3}, optical signal to noise ratio (OSNR) in multi-channel regeneration output can improve 0.5 – 1 dB from Fig. 5(a) and more than 3 dB from Fig. 5(b). Under the condition of high noise, Fig. 5(c) shows that back-to-back (b2b) system is deteriorative tremendously and BER even cannot reach 10^{-2}. In contrast, the BER of multi-channel regeneration system is still very well and can reach 4.43×10^{-8}.

It can be seen from both constellations and BER results that the regeneration performance of the four QPSK signals is very similar, but not the same. The possible reasons are as follows. First of all, to emulate noise in a real transmission system, we add both white noise and phase noise into our simulation device. Although, they are the same at first, but noise changes randomly during transmission system which can make a little difference

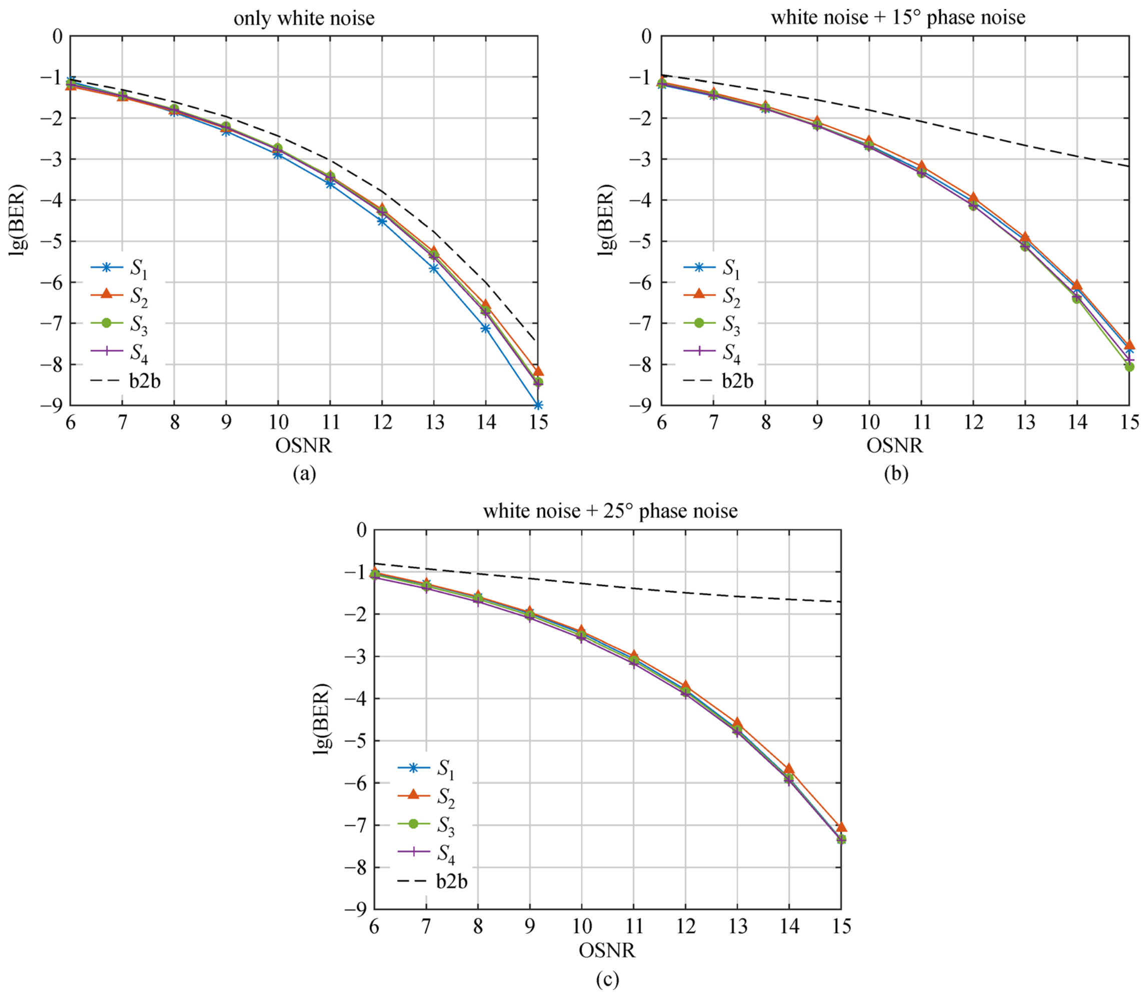

Fig. 5 BER of input and output signals with (a) only white noise; (b) white noise and 15° phase noise; (c) white noise and 25° phase noise

among the four channels. Secondly, although the parameters of fiber are set the same, but the efficiency of four wave mixing in the fiber will be some difference because it cannot be controlled precisely. In the end, the dispersion in the fiber also has a slight effect on the regeneration result. The zero-dispersion-wavelength to the center frequency of each signal is different which can also make a little difference to the four channels.

Taking S_1 for example, we compare the BER among multi-channel, single channel and back-to-back system in Fig. 6. The results suggest that the multi-channel system's regeneration effect is close to single channel and both of them can make a lot of improvements compared with back-to-back system especially under the condition of high noise. Compared the multi-channel system to the single channel, the regeneration effect is a little bit worse. This is consistent with the theoretical derivation. Because of the multi-channel transmission system, it is inevitable for the four signals that will introduce a little crosstalk compared with single channel transmission system. When it comes to our regeneration device, although the stage of coherent addition is not in the nonlinear medium which can completely avoid the crosstalk between signals and harmonics, the generation of harmonic is inevitable to use four wave mixing in HNLF. The main crosstalk in our regeneration system occurs in HNLF. It can be summarized as the following points. First of all, in the two HNLF to generate the conjugates and second harmonics, the nonlinear crosstalk is introduced between the two reverse transmission signals. Besides that, in the final HNLF to generate the four high-order conjugates $-3\varphi_{\mathrm{in}}$, the crosstalk comes from two aspects. On the one hand, the two signals transmitted in the same direction (S_1, S_3 and S_2, S_4) will have relatively strong nonlinear crosstalk. On the other hand, the reverse transmission of signals will also bring a trace of crosstalk. However, seeing from Fig. 6, it can be find that all the crosstalk mentioned above does not have much impact on our regeneration system.

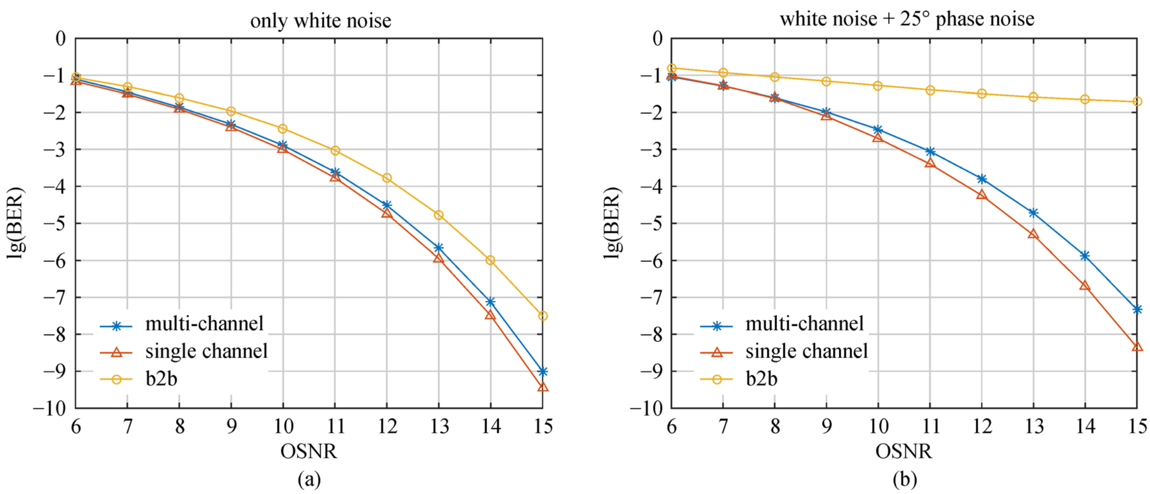

Fig. 6 BER comparison among multi-channel, single channel and back-to-back with (a) only white noise; (b) white noise and 25° phase noise

5 Conclusion

In this paper, we put forward a novel scheme to simultaneously regenerate four different channels of QPSK signal based on phase sensitive amplification. We use four wave mixing to generate the three harmonic conjugates and optical combiner to realize phase regeneration by coherent addition. The signal constellation as well as BER demonstrate the identical regeneration effect among different channels and improve a lot compared with back-to-back system. It has been show that OSNR can improve morn then 3 dB while BER reaches 10^{-3} under a constant white noise and 15° phase noise. In summary, the regeneration effect is more obvious while the noise is higher.

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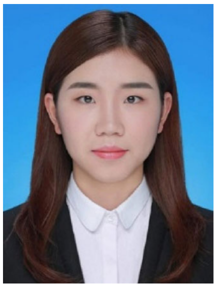

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