Simultaneous format conversion of parallel multichannel based on FWM in symmetric highly nonlinear fiber loop

Yueying Zhan (展月英), Min Zhang (张　民)*, Zhuo Liu (刘　卓), and Xue Chen (陈　雪)

State Key Laboratory of Information Photonics and Optical Communications,
Beijing University of Posts and Telecommunications, Beijing 100876, China
**Corresponding author: m zhany@bupt.edu.cn*

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A parallel multichannel format conversion scheme for elastic optical networking based on four wave mixing (FWM) in symmetric highly nonlinear fiber loop (S-HNLF-L) is proposed and the performance is evaluated and discussed. Parallel four channels format conversion from quadrature phase shift keying (QPSK) to binary phase shift keying (BPSK) signals at 40 Gb/s is theoretically analyzed and simulated. The results are helpful for the format-adaptive elastic optical networks.

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Elastic optical networking (EON) has emerged in recent years as a promising solution for implementing flexible bandwidth channels (flex paths) that efficiently match the allocated bandwidth with the traffic demand using agile granularities of spectrum allocation[1−3] and multi-wavelengths optical processing has also been recognized as one of the enabling technologies to advance the future EON[3−5]. The optical format conversion is an essential function to provide flexible management and interface for different networks. Though optical format conversion has been extensively studied, but mainly focused on the format conversion of single channel, like nonreturn-to-zero (NRZ) signal to binary phase shift keying (BPSK) or quadrature phase shift keying (QPSK) signal, QPSK signal to BPSK signal, and 8 phase shift keying (8PSK) signal to QPSK signal[6−10]. Recently, several schemes of multi-channels format conversion are proposed[5,11−13], such as from NRZ-QPSK/return-to-zero (RZ)-QPSK to RZ-QPSK/NRZ-QPSK, multichannel (carrier-suppressed) RZ-DPSK signals conversion and parallel eight channels from NRZ to RZ format conversion using semiconductor optical amplifier (SOA) and/or a delay interferometer (DI). These schemes provide flexibility and multi-channel processing for future network interface. Therefore, all-optical format conversion for multi-channel signals is a promising technology, since it helps reduce implementation costs and removes the bottleneck in ultrafast signal processing without requiring costly optical-electrical-optical equipment for the elastic optical networks[13,14]. However, there have been a few parallel multichannel to MPSK and/or quadrature amplitude modulation (QAM) conversion demonstrations, and it is not accommodate the evolution of the next generation optical networks.

We demonstrate parallel four channels format conversion from QPSK to BPSK signals based on four wave mixing (FWM) using a symmetric highly nonlinear fiber loop (S-HNLF-L). The performances for the four channel input QPSK signals and output BPSK signals are investigated, and around 3.1-dB sensitivity improvement is obtained after the conversion. And the proposed scheme could be scaled to eight or more wavelength division multiplexing (WDM) channels with the format conversion of the advanced modulation formats.

Figure 1(a) illustrates such a network with an elementary two-node configuration where each node is capable of supporting various modulation formats. The performances of the received signal from node B is impairments when the transmission is longer and the signals are higher-level format, such as QPSK, 16QAM, 32QAM,

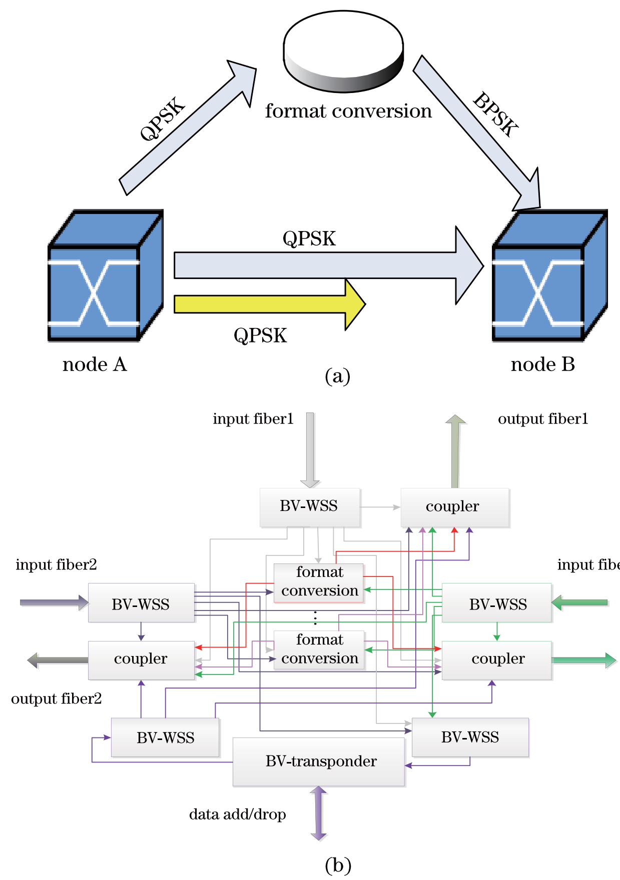

Fig. 1. (a) Illustration of an elementary two-node flexible-bandwidth network; (b) CDCG multi-degree ROADM configurable based on format conversion. BV: bandwidth variable.

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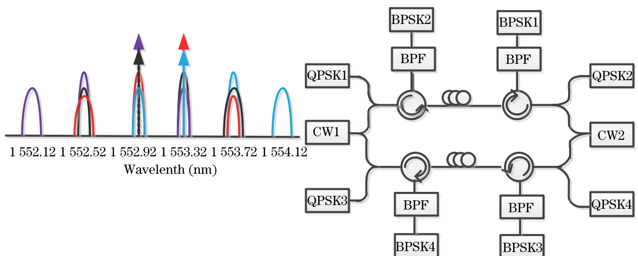

(a) (b)

Fig. 2. (a) Wavelength position and (b) operation principle of the proposed parallel four channels format conversion system. BPF: bandpass filter.

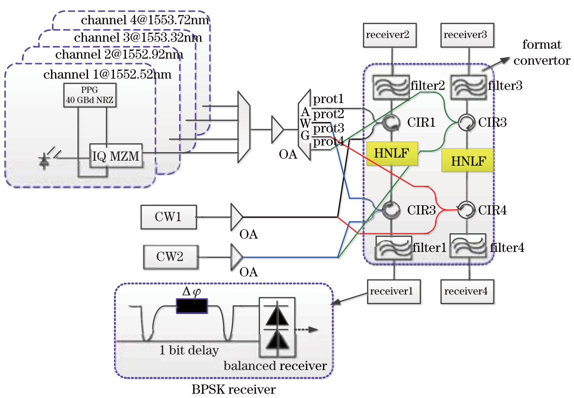

Fig. 3. Simulation setup for parallel four channels QPSK signals format conversion. CIR: circulator; OA: optical amplifier; PPG: programmable pulse generator.

and so on. Therefore, in order to improve performance and robustness to different transmission impairments form node A to node B, the optical format conversion is an essential function in providing flexible management and interface for different networks like Fig 1(a), which utilize a format convertor between node A and node B to realized error free transmission. Figure 1(b) shows a broadcast and select-based colorless, directionless, contentionless, and gridless (CDCG) multi-degree reconfigurable optical add-drop multiplexer (ROADM) with mainly optical power splitters and wavelength selective switches (WSSs) based on format conversion, which can flexibly adjust the format to support the required performance of the EON[15−17].

The wavelength position and the operation principle of the proposed scheme for parallel four QPSK signals convert to BPSK signals based on FWM in S-HNLF-L is shown in Fig. 2 and the electrical field of the two new sidebands E_{112} and E_{221} of the channel1 after FWM process are given by[17]

$$\begin{aligned} E_{112} &= k_{112} E_{\mathrm{CW1}}^2 E_{\mathrm{QPSK}}^* \mathrm{e}^{\mathrm{j}[2\pi(2f_1-f_2)t+(2\varphi_1-\varphi_2)]} \\ &= k_{112} P_{\mathrm{CW1}} \sqrt{P_{\mathrm{QPSK}}} \mathrm{e}^{\mathrm{j}[2\pi(2f_2-f_1)t+2\varphi_2)]}, \end{aligned} \quad (1)$$

$$\begin{aligned} E_{221} &= k_{221} E_{\mathrm{QPSK}}^2 E_{\mathrm{CW1}}^* \mathrm{e}^{\mathrm{j}[2\pi(2f_2-f_1)t+(2\varphi_2-\varphi_1)]} \\ &= k_{221} P_{\mathrm{QPSK}} \sqrt{P_{\mathrm{CW1}}} \mathrm{e}^{\mathrm{j}[2\pi(2f_2-f_1)t+2\varphi_2)]}, \end{aligned} \quad (2)$$

where f_i and $\varphi_i (i \in [1,2])$ are the frequency and the phase of the input signals; E_{CW1}, E_{QPSK}, P_{CW1}, and P_{QPSK} are the electrical field and the amplitude of the one of the QPSK signals, respectively; k is a constant proportional to the FWM efficiency. The frequency of the generated sidebands are $(2f_1 - f_2)$ and $(2f_2 - f_1)$, respectively. The phase of the generated idler at f_{221} is $(2\varphi_2)$ and the idler is filtered by a tunable optical filter (TOF) and then the BPSK signal is converted[17]. Figure 2(a) shows wavelength position of the input signals output signals for four channels is 0.4 nm and the frequency spacing of the signals is 50 GHz. QPSK1 signal and QPSK3 signal have same pump signal CW1, while QPSK2 signal and QPSK4 signal have the same pump signal CW2. Figure 2(b) shows the all-optical format conversion scheme for four channel QPSK signals to BPSK signal based on FWM in S-HNLF-L. The S-HNLF-L consists two pieces of HNLF, four circulators, four filters, and several couplers. Two counter-propagating QPSK1 and QPSK2 signals and CW1 and CW2 light are injected into the HNLF which locates upper arm in S-HNLF-L, meanwhile, the other two counter-propagating QPSK3 and QPSK4 signals and CW1 and CW2 light are injected into the HNLF which locates lower arm in S-HNLF-L. QPSK1 and QPSK3 signals with the same pump signal CW1, and QPSK2 and QPSK4 signals with the same pump signal CW2. The idlers generated after FWM process in the HNLFs are passed four circulators and the idlers which are BPSK signals are filtered by four different TOFs. Therefore, the four channels QPSK signals can be converted to four BPSK signals.

The simulation platform used in the letter is VPITransmissionMakerTM$^{8.5}$ Optical Systems. The simulation setup for parallel four QPSK signals format conversion system is shown in Fig. 3. The setup includes the generation of four QPSK signals, two pump signals CW1 and CW2, format convertor and the receivers of the converted BPSK. Four optical sources, all the average powers of -8.15 dBm and working at 1552.52 nm (channel 1), 1552.92 nm (channel 2), 1553.32 nm (channel 3), and 1553.72 nm (channel 4), are modulated to four RZ-QPSK signals by four 40-Gb/s de-correlated and amplified electrical PRBS signal with a sequence length of 2^{15}-1 through a dual-parallel Mach-Zehnder modulator (DP-MZM). After amplification, the QPSK signals on the four channels are wavelength de-multiplexed with an arrayed waveguide grating (AWG). Then the QPSK signal on channel 1 and the CW1 light of 1552.92-nm wavelength and -8-dBm power are mixed and injected into the HNLF1 after the circulator1, while the QPSK

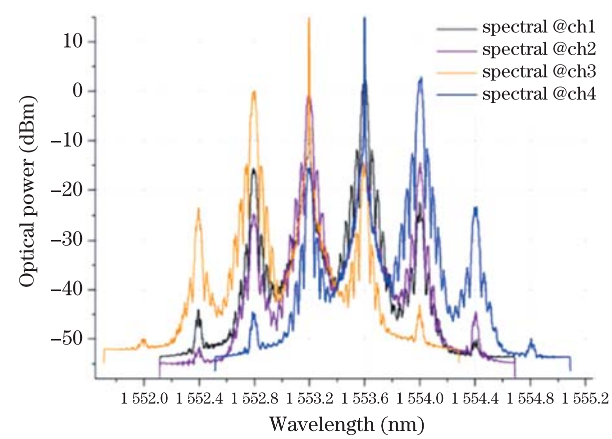

Fig. 4. Measured optical spectrum after HNLF in the format conversion simulation from QPSK to BPSK.

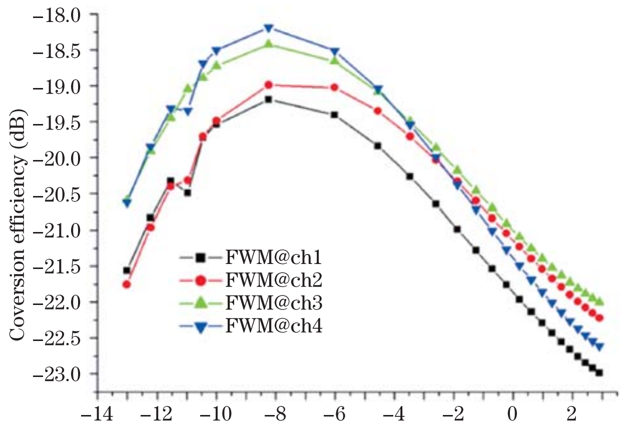

Fig. 5. Conversion efficiency of four channels at different pump signal powers.

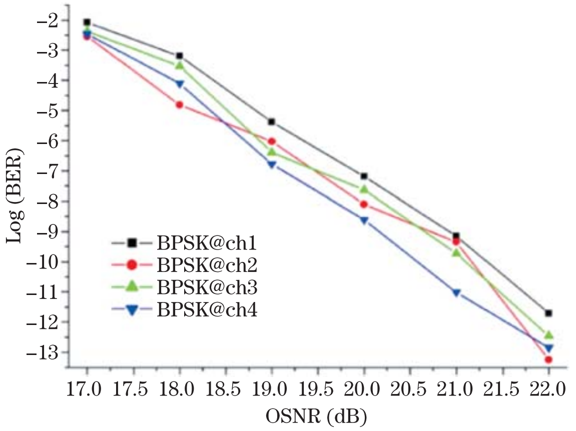

Fig. 6. Received BER versus input OSNR for four received BPSK signals.

signal on channel2 and the other CW2 light of 1553.32-nm wavelength and -8-dBm power are mixed and injected into the HNLF1 at counter-propagating direction after the circulator2 simultaneously. Circulators placed on both side of the 200-m HNLF (zero-dispersion at 1553.3 nm, dispersion slope S=0.017 $\mathrm{ps \cdot nm^{-2} \cdot km^{-1}}$, and nonlinear coefficient is 10.5 $\mathrm{W^{-1}km^{-1}}$) are used to separate the counter-propagating signals in the fiber. Meanwhile, the QPSK signal on channel 3 and the CW1 light are injected into the HNLF2 and the channel 4 QPSK signal and CW2 light are injected into HNLF2 at counter direction. And the FWM processes are happened in HNLF1 and HNLF2. Therefore, the converted BPSK signals of the parallel four channels were detected by a balanced receiver after passing through a 1-bit DI which is shown in Fig. 3.

The corresponding optical spectra of four channels after the HNLFs for the conversion from QPSK to BPSK is depicted in Fig. 4 and the results are in good agreement with the theoretical results. Though the wavelength of converted BPSK signals of channel 1 and channel 4 are same to CW1, CW2, QPSK2, and QPSK3, there are no interferences among of them because the processing of the system are paralleled.

The conversion efficiency, defined as $\eta = P_c(L)/P_s(0)$, is an important factor in evaluating the performance of the frequency conversion, and is influenced by many parameters, such as the input pump powers and the frequency spacing between pump and signal[18]. In this letter, it is defined as the optical power ratio between the FWM product which is the BPSK signal and the input QPSK signal. Here, we focus on the conversion efficiency at different pump powers. Figure 5 shows the conversion efficiency of the four channels at different pump power, in our system, pump1 and pump2 have the same power. From the measured results, the maximum conversion efficiency of the four channels is achieved when the pump power at -8 dBm and the conversion efficiencies of channel 2 and channel 4 are larger than channel 1 and channel 3 due to the features of the HNLF. The turning point of the results is due to the limitation of the system.

Figure 6 indicates that the BER of the proposed four channels format conversion system improves with the increase of OSNRs of the converted BPSK optical signals. As the results, the OSNR should be larger than 20 dB and the received BPSK signal can be error-free operation for the parallel four channels format conversion system. The measured BER performances of the input QPSK signals and the converted BPSK signals are plotted in Fig. 7, which shows approximately 3.1-dB sensitivity difference between the converted BPSK signals and the input QPSK signals. Figure 8 shows the demodulated eye diagrams of the QPSK and BPSK signals for parallel four channels at BER of 10^{-9}.

According to the preceding discussion, we give some useful information on parameter choice regarding the performance of the format conversion. The proposed parallel multi-channels format conversion scheme is simple, cost-efficient, and scaled. The parallel four channels

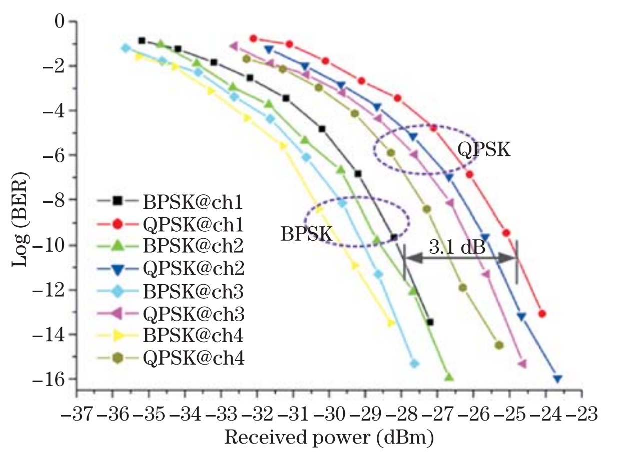

Fig. 7. Measured BER versus received power for four QPSK and BPSK signals.

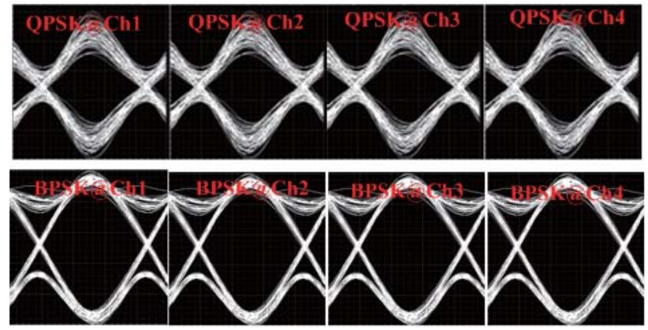

Fig. 8. Demodulated eye diagrams of converted BPSK signals for parallel four channels.

format conversion between optical QPSK and BPSK signal was proposed and it could be scaled to format conversion from MPSK signal to (M/2)PSK or much more channels. With values of the other factors fixed, to get the maximum conversion efficiency, the power of pump2 powerP_2 should be same as pump1; moreover, increases with pump power, and increase slows when the power >-8 dBm. The OSNR of the input optical signal should be larger than 20 dB at least for error-free generation and transmission.

In conclusion, we propose and evaluate a parallel four channels format conversion from QPSK to BPSK signals based on FWM in a S-HNLF-L. The performances for the four channels input QPSK signals and output BPSK signals are investigated, and around 3.1-dB sensitivity improvement is obtained after the conversion. An adaptive format conversion and management scheme for EON is presented.

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