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Performance Analysis of All-Optical Wavelength-Shift-Free Format Conversion from QPSK to Two BPSK Tributaries Using FWM and Interference

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SUMMARY Conversion between multi-level modulation formats is one of key processing functions for flexible networking aimed at high spectral efficiency (SE) in optical fiber transmission. The authors previously proposed an all-optical format conversion system from binary phase-shift keying (BPSK) to quadrature PSK (QPSK) and reported an experimental demonstration. In this paper, we consider its reversed conversion, that is, from QPSK to BPSK. The proposed system consists of a highly nonlinear fiber used to generate complex conjugate signal, and a 3-dB directional coupler used to produce converted signals by interfering the incident signal with the complex conjugate signal. The incident QPSK stream is converted into two BPSK tributaries without any loss of transmitting data. We show the system performances such as bit-error-rate and optical signal-to-noise ratio penalty evaluated by numerical simulation.

key words: *optical processing, modulation format, four-wave mixing, QPSK, BPSK*

1. Introduction

To meet the demand in rapidly growing communication traffic, advanced modulation formats have been employed to increase transmission capacity and spectral efficiency (SE) in optical fibers with developing digital signal processing capability [1], [2]. In such spectrally efficient networks, flexible conversion between different levels of multi-level modulation formats without using optical-to-electrical (O/E) and electrical-to-optical (E/O) conversions will be important to improve utilization of fiber's spectral resource and to suppress power consumption in network nodes.

Various all-optical techniques have been studied for modulation format conversion from lower-order to higher-order to increase spectral efficiency. For example, from on-off-keying (OOK) to binary phase-shift keying (BPSK), quadrature PSK (QPSK), or 8 PSK have been reported using nonlinear effects in a semiconductor optical amplifier (SOA) and a highly nonlinear fiber (HNLF) [3], [4]. Among different m-ary PSKs, the authors proposed passive interference method to convert from BPSK to QPSK [5], and the same principle was further applied to convert to quadrature amplitude modulation (QAM) by Parmigiani *et al.* [6].

In this paper, we consider its reverse conversion, that is, from QPSK to BPSK. Such reverse conversion from higher-order to lower-order is needed when the signal transmitted in long-haul is then destined to local or short-reach transmission. To convert from QPSK to BPSK, various nonlinear methods have been reported. Conversion using phase erasure by four-wave mixing (FWM) [7], using phase squeezing by phase-sensitive amplification PSA) in HNLF or periodically poled lithium niobate (PPLN) [8], and using phase-sensitive FWM in HNLF [9] or PPLN [10] have been reported. Among these methods, the first one using phase erasure outputs only a half of the original data sequence as a BPSK stream with a single pump light. The second method generates either of the two BPSK tributaries by setting 0 or $\pi/2$ phase-shift in the incident QPSK sequence, where two pump lights are required. On the contrary, the third method generates two BPSK tributaries without loss of the original data; however, four phase-arranged pump lights are required. In these three methods, the incident QPSK stream and output BPSK streams have different wavelengths. This wavelength difference is inefficient because it might need additional wavelength conversion when a signal once isolated for format conversion is re-inserted into the same wavelength channel among other WDM channels.

Some conversion techniques with no signal center wavelength shift have been reported so far to solve the issue. Experimental demonstration using dual-pump PSA [11] demultiplexed each phase component of a QPSK signal separately. Our previously reported method [12] converted a QPSK signal to two BPSK tributaries simultaneously without loss of the original data by using FWM, in which the quantitative analysis based on bit-error-rate (BER) was limited on the comparison between the nonlinear media of HNLF or SOA. Recently proposed conversion method [13] includes experimental results and is expected to be more stable by using polarizers, though, the experimental analyses were mainly performed based on constellation diagrams.

In this paper, we describe the concept and detailed operation principle of the proposed format conversion from QPSK to BPSK as well as quantitative analyses based on

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BER such as dependencies of signal OSNR, pump power, laser linewidth, pulse shape, and symbol rate by numerical simulation in order to assess the conversion system performance. Moreover, issues to be considered for practical use of the proposed system are also discussed.

2. Operation Principle

The proposed format conversion system is schematically illustrated in Fig. 1. The setup consists of two stages, that is, one is for generating the phase conjugate of the incident QPSK signal, and another is to interfere the input QPSK signal with the generated phase conjugate signal. An incident QPSK sequence $\boldsymbol{E}_s$ is combined with orthogonally polarized two pump signals $\boldsymbol{E}_{p1}$ and $\boldsymbol{E}_{p2}$, and these signals are incident in a HNLF. The incident QPSK signal with angular frequency ω_s $(= 2\pi f_s)$ in the HNLF is written as

$$\begin{aligned} \boldsymbol{E}_s(t,z) &= \boldsymbol{e}_x \frac{E_s}{\sqrt{2}} e^{j(\omega_s t - \beta_s z)} \sum_i f_0(t - i\Delta T) \\ &\quad \times \left[e^{j(\phi_{Ii} + \pi/2)} + e^{j\phi_{Qi}} \right] \\ &= \boldsymbol{e}_x E_s e^{j(\omega_s t - \beta_s z)} \sum_i f_0(t - i\Delta T) e^{j\phi_i}, \end{aligned} \tag{1}$$

where $\boldsymbol{e}_x$ is the unit vector in x polarization, E_s is the real-valued amplitude, j is the imaginary unit, $f_0(t)$ denotes a pulse shape, β_s is the propagation constant, ϕ_{I_i} and ϕ_{Q_i} are the in-phase and the quadrature phase of ith data sequence, respectively, and ΔT is the pulse period. The QPSK phase ϕ_i is derived as given by

$$\phi_i = \arctan \left[\frac{\sin(\phi_{I_i} + \pi/2) + \sin(\phi_{Q_i})}{\cos(\phi_{I_i} + \pi/2) + \cos(\phi_{Q_i})} \right]. \tag{2}$$

The two continuous wave (CW) pump signals with angular frequencies ω_{p1} $(= 2\pi f_{p1})$ and ω_{p2} $(= 2\pi f_{p2})$ in orthogonal polarization states are given by

$$\begin{aligned} \boldsymbol{E}_{p1}(t,z) &= \boldsymbol{e}_x E_{p1} e^{j(\omega_{p1} t - \beta_{p1} z)}, \\ \boldsymbol{E}_{p2}(t,z) &= \boldsymbol{e}_y E_{p2} e^{j(\omega_{p2} t - \beta_{p2} z)}, \end{aligned} \tag{3}$$

where β_{p1} and β_{p2} are the propagation constants and the pump angular frequencies are chosen to be $\omega_{p1} + \omega_{p2} = 2\omega_s$ to induce FWM with the same signal center frequency [14].

By considering the phase matching condition, $\beta_{p1} + \beta_{p2} = 2\beta_s$, the generated optical field $\boldsymbol{E}_F$ at the output of the HNLF at $z = L$ is given by

$$\boldsymbol{E}_F = \boldsymbol{e}_y \kappa E_s E_{p1} E_{p2} e^{j(\omega_s t - \beta_s L)} \sum_i f_0(t - i\Delta T) e^{-j\phi_i}, \tag{4}$$

where κ is the conversion efficiency, E_s and $e^{-j\phi_i}$ correspond to the real-valued amplitude and the complex conjugate phase term of the incident signal, respectively. The generated phase conjugate signal $\boldsymbol{E}_F$ is phase shifted by $\pi/2$ to be $\boldsymbol{E}'_F = \boldsymbol{E}_F e^{j\pi/2}$. The original signal $\boldsymbol{E}_s$ is attenuated by $\alpha = \kappa E_{p1} E_{p2}$ with the attenuator, and its polarization is rotated to be

$$\boldsymbol{E}'_s = \boldsymbol{e}_y \alpha E_s e^{j(\omega_s t - \beta_s L)} \sum_i f_0(t - i\Delta T) e^{j\phi_i}. \tag{5}$$

We obtain two outputs from the 3-dB coupler as given by

$$\begin{aligned} \begin{pmatrix} \boldsymbol{E}_{\text{out1}} \\ \boldsymbol{E}_{\text{out2}} \end{pmatrix} &= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -j \\ -j & 1 \end{pmatrix} \begin{pmatrix} \boldsymbol{E}'_F \\ \boldsymbol{E}'_s \end{pmatrix} \\ &= \boldsymbol{e}_y \sqrt{2} \alpha E_s e^{j(\omega_s t - \beta_s L)} \sum_i f_0(t - i\Delta T) \begin{pmatrix} \sin\phi_i \\ \cos\phi_i \end{pmatrix}. \end{aligned} \tag{6}$$

The output signals correspond to the two converted BPSK signals as shown in Table 1. The constellation of the incident QPSK code and the output BPSK codes are illustrated in Fig. 2.

It is worth noting that this conversion is assumed to be performed separately from the transmission fiber. Therefore, there is no concern about a certain bandwidth occupation by pump and FWM-product waves even for applying to WDM signals because each of them would be demultiplexed in advance and then converted as the channel-by-channel manner.

Table 1 Incident phase ϕ_i and the outputs.

$I_i = \phi_{Ii}/\pi$	$Q_i = \phi_{Qi}/\pi$	ϕ_i	$\sin\phi_i$	$\cos\phi_i$
0	0	$\pi/4$	1	1
0	1	$3\pi/4$	1	−1
1	1	$5\pi/4$	−1	−1
1	0	$7\pi/4$	−1	1

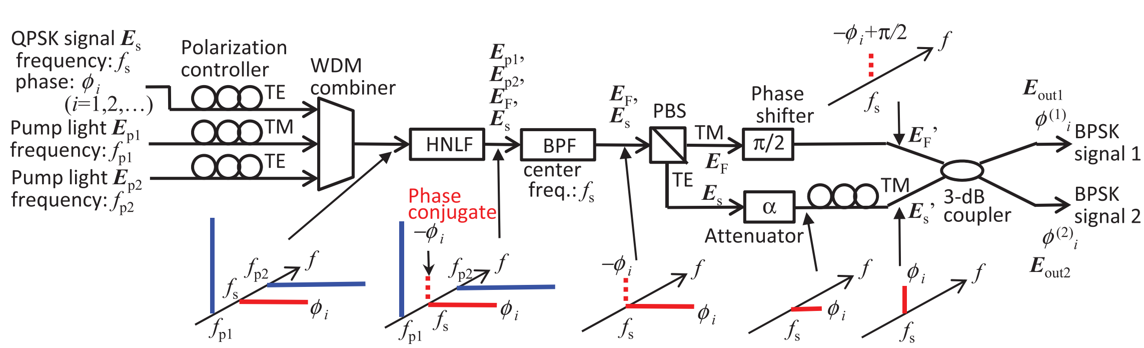


Fig. 1 All-optical wavelength-shift-free modulation format converter from a QPSK stream to two BPSK tributaries using FWM in a HNLF.

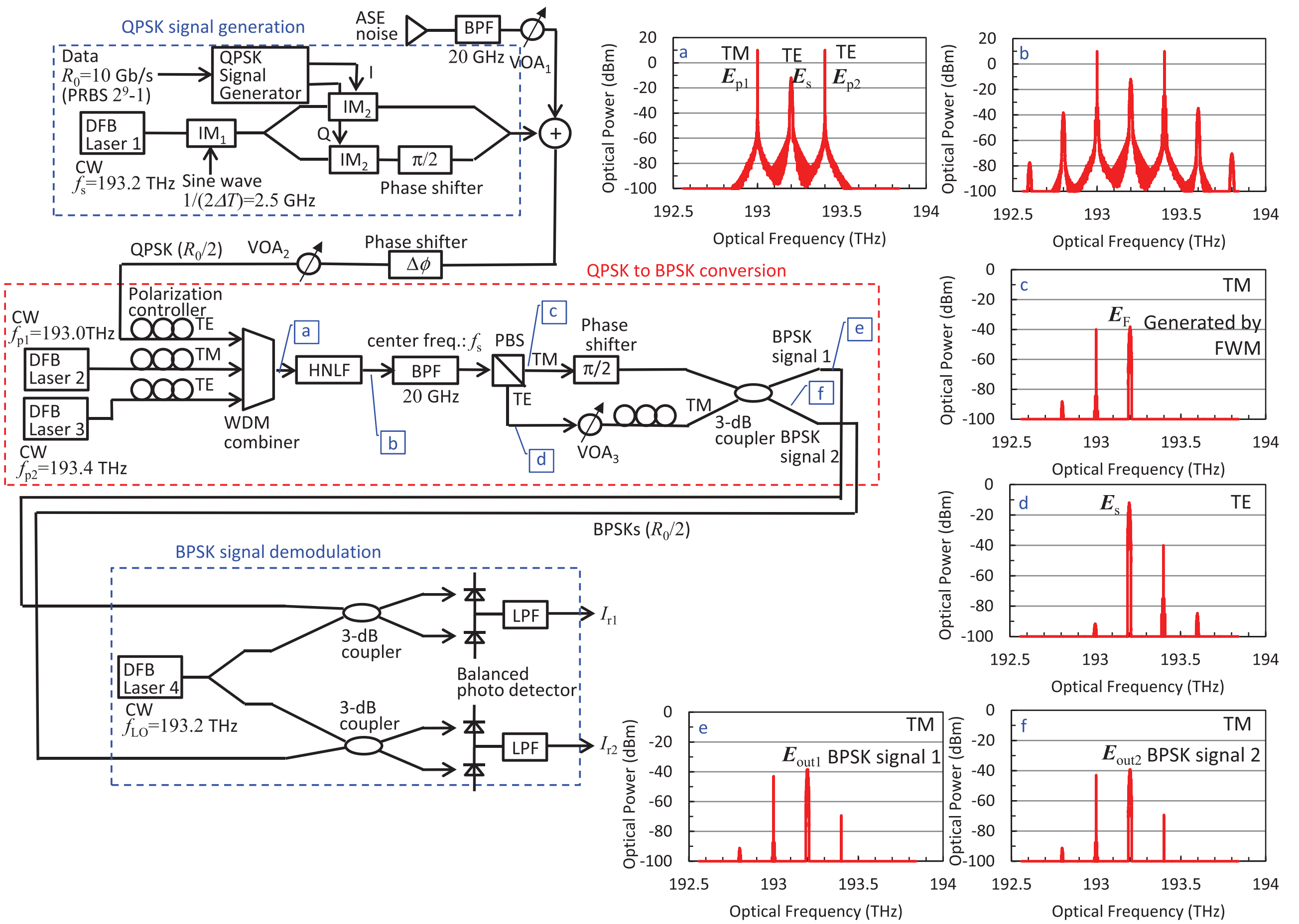


Fig. 3 Setup used in numerical simulation. Optical spectra are shown as insets.

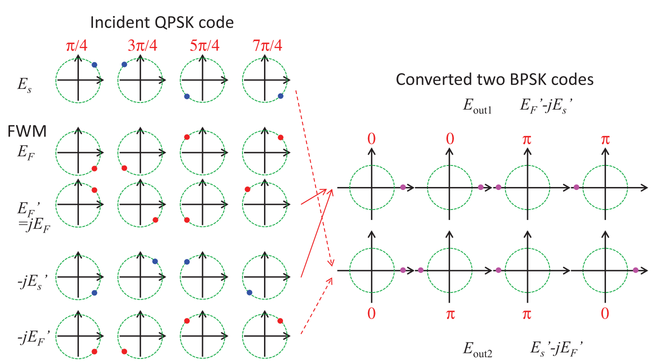


Fig. 2 Constellation of each incident QPSK code and the converted BPSK codes.

3. Numerical Simulation

The proposed format conversion is demonstrated by numerical simulation using OptiSystem (Optiwave Systems Inc.). The system model is shown in Fig. 3. The RZ QPSK signal at 5 Gbaud is generated using a 10-dBm laser source at f_s = 193.2 THz. The pump lasers have power of 10 dBm at f_{p1} = 193.0 THz and f_{p2} = 193.4 THz. The local laser source at the coherent detection has power of 5 dBm at $f_{LO} = f_s$. All the laser sources are assumed to have linewidth of 100 kHz. We assume that these laser sources are phase-locked in order to keep the phase matching condition between the signal and the pump laser sources, and to avoid frequency offset error between the signal and the local laser sources. A discussion on how this can be achieved will be given in Sect. 4. An ASE noise is added in both polarizations before format conversion to measure bit-error-rate (BER) performance. The WDM combiner has bandwidth of 100 GHz. The HNLF has length of L = 100 m with nonlinearity $n_2 = 2.7 \times 10^{-20}$ m^2/W [15]. The zero-dispersion wavelength is 1550 nm with dispersion slope of 0.075 ps/nm^2/km. The band-pass filter (BPF) after the HNLF has a rectangle-shape transmission function with width of 20 GHz centered at f_s and sideband suppression of 50 dB. The filtered signal is sent to the polarization beam splitter (PBS) to be separated in TE and TM polarizations. The variable optical attenuator (VOA$_3$) is adjusted so that the intensity of the phase conjugate signal in TM mode is equal to that of the original signal in TE mode. The phase conjugate signal is phase-shifted by $\pi/2$ and coupled with the polarization converted original signal to generate two BPSK signals. These two BPSK signals are demodulated using coherent receivers with output currents I_{r1} and I_{r2}.

Optical spectra at some points of the conversion system are also shown as insets. In order to obtain higher FWM conversion efficiency, we set the signal wavelength to nearly zero-dispersion wavelength of HNLF. The FWM conversion efficiency from the incident signal to the phase conjugate signal is −26.3 dB and −16.3 dB at a pump power of 10 dBm and 15 dBm, respectively.

Figure 4 shows the waveforms in the conversion circuit, where the linewidth of all the lasers was set at 0 Hz to show ideally converted waveforms. Two coded signals I and Q shown in (a) and (b) are generated using a QPSK precoder from a single pseudorandom binary sequence (PRBS) of $2^{15} - 1$ at bit rate of $R_0 = 10$ Gb/s. A modulated RZ QPSK signal $\boldsymbol{E}_s$ at symbol rate of $R_0/2$ is shown in (c). Two converted BPSK signals $\boldsymbol{E}_{\text{out1}}$ and $\boldsymbol{E}_{\text{out2}}$ are shown in (d) and (e), respectively. These two BPSK signals are detected by coherent balanced detectors as shown in (f) and (g) that coincide with the original I and inverse Q codes, respectively.

The evaluated BER performance as a function of OSNR of the original QPSK signal measured at the input port of the WDM multiplexer for the cases of pump power of 5 dBm, 10 dBm, and 15 dBm is shown in Fig. 5 (a). As a reference, a back-to-back BER performance without format conversion is also evaluated by directly detecting the noise-added QPSK signal with a coherent QPSK receiver. Two measured results, I_{r1} and I_{r2}, correspond to the I and Q signals, respectively. The signal power at the WDM combiner is 2.25 dBm. Even at low pump power of 5 dBm, error-free operation is achieved with high OSNR. Sample constellation maps of the original QPSK signal and the extracted two BPSK signals at pump power of 10 dBm are shown in Figs. 5 (b) and (c) when OSNR of original QPSK signal is 22 dB and 28 dB, respectively. The average amplitude of each signal is normalized to 1. It is found from these constellation maps that the OSNR degradation affects the signal quality of converted BPSK sequences.

The BER performance is also plotted as a function of the signal power at the WDM combiner in Fig. 6 (a), where pump power is 10 dBm and two values of OSNR, 25 dBm and 30 dBm, are assumed as a parameter. It is found that there is a noise floor for a given OSNR. These BER curves can be explained qualitatively by ASE noise and shot noise. In our simulation, the shot noise is dominant in the receiver photo detector due to the coherent detection in which sufficient power is always injected by the local laser source. Therefore, the slope of the BER curves at lower signal power in Fig. 6 (a) is caused mainly by the

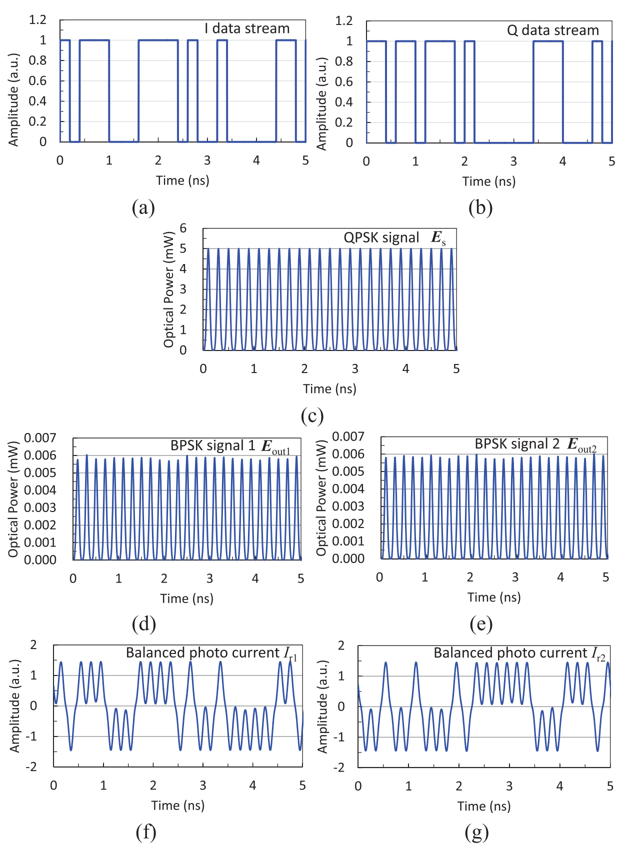


Fig. 4 Optical waveform through format conversion by HNLF; (a) NRZ I signal for QPSK modulation, (b) NRZ Q signal for QPSK modulation, (c) generated RZ QPSK signal, (d) converted BPSK signal 1, (e) converted BPSK signal 2, (f) balanced detected photo current I_{r1}, and (g) balanced detected photo current I_{r2}.

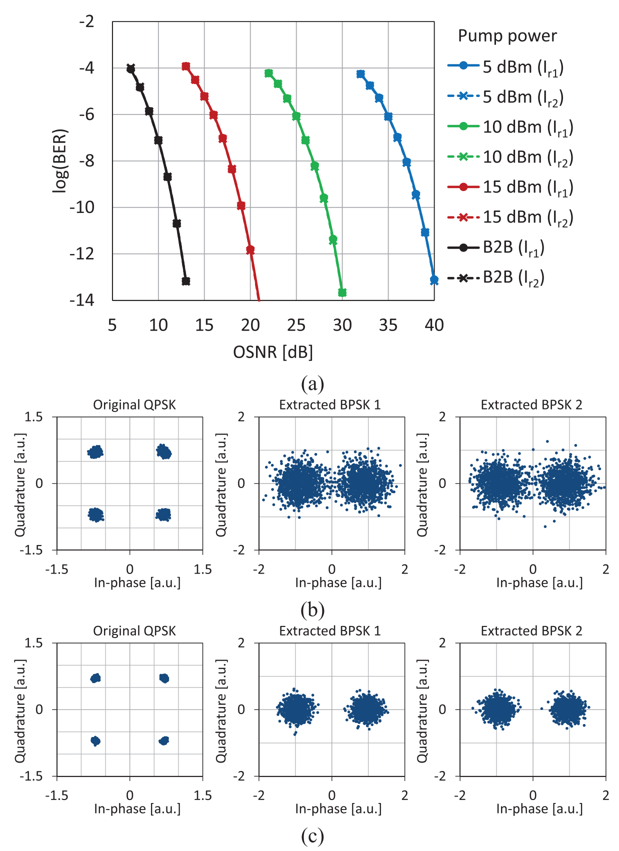
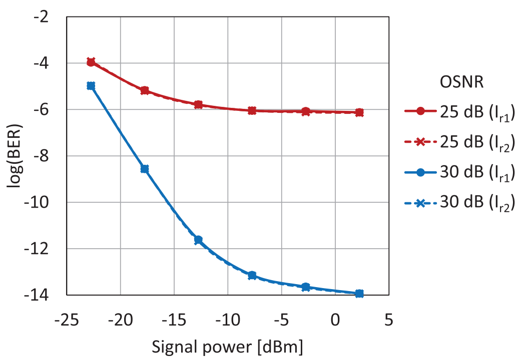
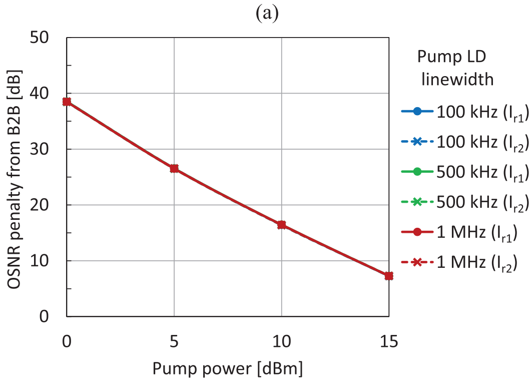


Fig. 5 BER performance and constellation examples of the format conversion; (a) BER as a function of OSNR with pump power of 5 dBm, 10 dBm, and 15 dBm, and the signal power of 2.25 dBm at the WDM combiner, (b) constellation map of original QPSK signal and extracted two BPSK signals at pump power of 10 dBm and OSNR of 22 dB, and (c) 28 dB.



(a)



(b)

Fig. 6 BER performance of the format conversion; (a) BER as a function of the signal power at the WDM combiner with pump power of 10 dBm, and (b) OSNR penalty from back-to-back result, where the linewidth of the pump lights is varied as a parameter.

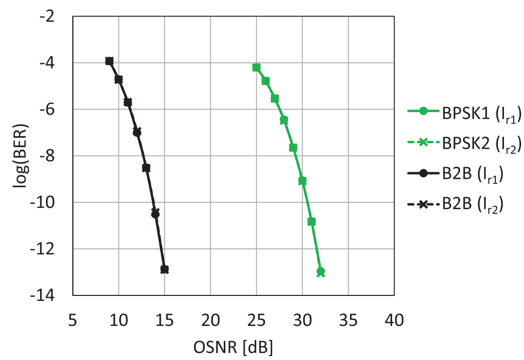


Fig. 7 BER performance of the format conversion for NRZ signals using 100-m HNLF, where the pump power is 10 dBm, and the signal power is 6.56 dBm at the WDM combiner.

shot noise, whereas the noise floor at higher signal power is caused dominantly by the given ASE noise.

The OSNR penalty from the back-to-back result at 10^{-9} BER is plotted as a function of pump power in Fig. 6 (b), where the linewidth of the two pump lights is varied as a parameter. The signal power is the same as in (a) and the pump power is 10 dBm. In addition to the constant noise floor for a given OSNR, the power of the phase conjugate signal depends on the pump power. Therefore, the OSNR penalty has a direct relation with the pump power. The OSNR penalty shows 7.3 dB from back-to-back result when the pump power is 15 dBm at any linewidths. Although the FWM efficiency at this pump power is −16.3 dB as described above, calculated OSNR penalty is 9-dB lower than the value corresponding to the FWM efficiency. This difference can be explained by following three reasons. First of all, in order to achieve the same BER, QPSK format needs to have 3-dB higher energy than that of BPSK format in principle because QPSK has two bits in a single symbol. Second, we have used an extra optical splitter in frontend module to detect in-phase and quadrature components separately in the back-to-back QPSK measurement, resulted in 3-dB power loss. Final reason is the unbalance of the ASE noise level between the original QPSK signal and the complex conjugate QPSK signal. In our simulation, 10^{-9} BER is obtained at 15-dBm pump power and 2.25-dBm QPSK signal on TM polarization with 18.4-dB OSNR. The ASE noise added to the original QPSK signal on each polarization is on the power level of $2.25 - 18.4 - 3 = -19.15$ dBm(/0.1 nm). In this case, complex conjugate QPSK signal is generated at $2.25 - 16.3 = -14.05$ dBm on TE polarization due to the FWM efficiency. This complex conjugate QPSK signal is mixed with the ASE noise which has already been on TE polarization, namely, −14.05-dBm complex conjugate signal and −19.15-dBm(/0.1 nm) ASE noise. On TM mode, original QPSK signal is just attenuated on the same power level of −14.05 dBm without OSNR penalty. Therefore, combining the TE polarization component having 16.3-dB OSNR penalty due to the FWM efficiency with TM polarization (which is rotated to be TE polarization in advance) component having no OSNR penalty results in almost 3-dB decrease of OSNR penalty on the converted BPSK signals. Thus, above three reasons lead to 9-dB lower OSNR penalty. In other pump power case, OSNR penalty increases almost in steps of 10-dB corresponding to the FWM efficiency decrease due to the total pump power decrease. In addition, the OSNR penalty does not depend on the laser linewidth because all laser source is assumed to be phase-locked in our simulation.

We demonstrate the format conversion for QPSK signal in NRZ form with the setup without the intensity modulator (IM_1) in Fig. 3. The simulated result of BER performance is shown in Fig. 7, where pump power is 10 dBm and the signal power is 6.56 dBm at the WDM combiner. The OSNR at BER of 10^{-9} is about 30 dB and the OSNR penalty from the back-to-back result is 17 dB. The OSNR penalty is almost the same as that for RZ signals.

The OSNR penalty from the back-to-back result as a function of the symbol rate is plotted in Fig. 8 where the symbol rates of the QPSK signal are set to 5, 8, 16, 24, and 32 GBaud. The bandwidth of the BPF after the HNLF is changed to 100 GHz in these cases. The pump lasers have power of 10 dBm. The OSNR penalty shows almost the same value, therefore, no additional performance degradation is produced by the symbol rate change.

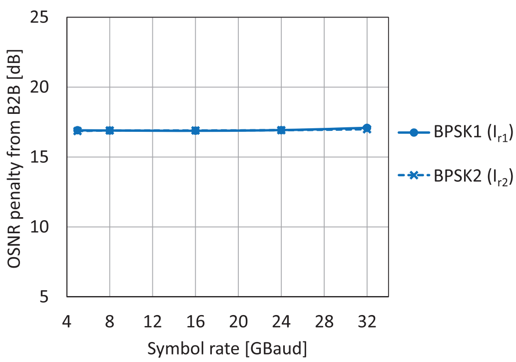


Fig. 8 OSNR penalty from back-to-back result as a function of the symbol rate 5, 8, 16, 24, and 32 Gbaud.

4. Discussion

In this section we discuss some important issues for practical use of the proposed conversion scheme. The first issue is about the phase-locking. There are two aspects of phase-locking that one is the need of phase-locked signal and pump laser sources and another is stabilizing the interference between the signal and the phase conjugated signal. For the phase-locked laser sources, two pump lights can be locked, for example, by generating frequency comb from a common laser source. Phase-locking between signal and pumps should be stabilized faster than the phase fluctuation. A possible method has been reported [11] in which the output of an optical phase comparator has been used as the error signal in a phase-locked loop. For the stabilized interference between the signal and the phase conjugated signal, a possible solution is the photonic integrated circuit. Although simulations are performed with HNLF, any nonlinear media supporting the possibility of integration can be used such as SOA and silicon nanowires. By using such media, the QPSK-to-BPSK conversion block can be completely integrated from the WDM combiner until the output of the 3 dB coupler.

Then, we consider another issue for better performance, that is, conversion efficiency of the proposed method. The FWM efficiency depends on the total power of two pumps, fiber length and nonlinear coefficient of the HNLF. Lower limit of the FWM efficiency can be determined by OSNR of the incident QPSK signal as discussed in the result of OSNR penalty. At least almost equivalent value to the signal OSNR is needed. On the contrary, upper limit of the FWM efficiency can be dominated by stimulated Brillouin scattering (SBS). Beyond the SBS threshold, the pump power is not efficiently used for the conversion and the FWM efficiency is restricted [16].

At the end of the discussion section, the other important issue is mentioned regarding the system configuration and power consumption compared to electrical regeneration with O/E and E/O conversion. With respect to the system configuration for a single channel, as a different set of two DFB pump lasers is needed in our proposed method, the electrical regeneration method also needs at least the same number of lasers due to its coherent detection and retransmission in an optical transceiver. Although two parallel retransmission is needed for the electrical regeneration method because our method generates two BPSK streams simultaneously, such retransmission can be replaced with a polarization multiplexed system with a single optical laser source. For applying to WDM system, both methods can be scaled with the number of WDM channels because our method and the electrical regeneration method need channel-by-channel conversion block and channel-by-channel transceiver, respectively. With respect to the power consumption, it is hardly assessed because of the implementation dependence of electrical modules such as materials used, process rule of integrated circuits, clock speed, associated control mechanism and etc. From a viewpoint of the symbol rate, our method has a merit of being able to operate at any symbol rate without changes in pump power as shown in Fig. 8. Whereas the power consumption of the electrical regeneration method can be qualitatively proportional to the symbol rate because that of electrical logic circuits is also proportional to the clock speed. This topic will be further investigated in our future works for practical use of the proposed method.

5. Conclusion

We have proposed an all-optical modulation format conversion system from a QPSK signal to two BPSK signals by using FWM which is the nonlinear conversion process that allows us to operate with phase-modulated signals. The conversion does not accompany a frequency shift between the incident QPSK signal and the converted BPSK signals. The data sequence of the incident QPSK signal is fully converted to two BPSK sequences without any loss of data.

The performance of the proposed system have successfully been demonstrated by numerical simulation. The OSNR required for 10^{-9} BER is around 18.4 dB and 27.5 dB for pump power of 15 dBm and 10 dBm, respectively, for the 100-m HNLF. The dependence of the OSNR penalty on the linewidth of pump lasers has also been investigated. It does not depend on the linewidth because all laser source is assumed to be phase-locked in our simulation. The OSNR penalty on the symbol rate shows almost the same value, which results in no additional performance degradation by the symbol rate change.

Since the proposed system is, in principle, applied in polarization preserved networks, the conversion performance is affected by fluctuation of polarization state and polarization mode dispersion in transmission fibers. We will investigate polarization-insensitive system and polarization-diversity system as future works in order not only to overcome such a degradation but also to apply to modulation formats with polarization multiplexing. Taking the phase-locking mechanism into account is also another big issue to be investigated as our future works for practical use of the proposed system.

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