All-Optical Modulation Format Conversion Between OOK, QPSK and 8QAM

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***Abstract*—Modulation format conversion is useful when the signal is transmitted through networks employing different modulation formats. It is also expected to increase the spectral efficiency and reduce power consumption in network nodes by applying all-optical signal processing to the modulation format conversion. In this paper, we propose an all-optical modulation format conversion system between on-off keying (OOK), quadrature phase shift keying (QPSK) and 8-ary quadrature amplitude modulation (8QAM) using optical nonlinear effects in semiconductor optical amplifier (SOA) and optical threshold device. We also evaluate the conversion performances of the system by numerical simulation in terms of optical signal-to-noise ratio, optical signal power, and accumulated chromatic dispersion.**

***Index Terms*—Optical processing, modulation format, 8QAM, QPSK, OOK.**

I. Introduction

IN recent years, along with the development of digital signal processing technology to improve transmission capacity and spectral efficiency (SE), advanced modulation formats are adopted in optical fiber communication [1], [2] for efficient use of the bandwidth resource. An employed modulation format for a specific network usually depends on the desired transmission capacity, optical reach, and system cost. Thus, it may be different in networks such as access, metro, and backbone networks. When the optical signal is transmitted through different networks, modulation formats should be converted at intermediate network nodes. Conventional format conversions are usually performed via electrical signal, namely, once received electrical signal is then re-transmitted as optical signal with the other modulation format. All-optical modulation format conversion without using optical-to-electrical (O/E) and electrical-to-optical (E/O) conversion is a candidate solution to reduce such processing overheads of O/E, E/O conversion at intermediate network nodes.

Various all-optical signal processing techniques have been studied so far to realize modulation format conversion. For instance, conversion from binary phase shift keying (BPSK) to quadrature PSK (QPSK) using a delay line interferometer (DLI) [3], conversion from QPSK to 16-ary quadrature amplitude modulation (16QAM) using DLI and spectral shaping filter [4] have been proposed. By superposing amplitude different QPSK signals, conversions from OOK to 16QAM using cross phase modulation (XPM) and parametric amplification [5], and from QPSK to 64QAM using nonlinear wave mixing [6] have been proposed. This sort of low-order to high-order format conversion technique is suitable when the signals sent over short distances or local transmissions are redirected to an extended long distance transmission. In the conversion method to 8QAM format, studies based on four wave mixing (FWM) in highly nonlinear fiber (HNLF) [7] and using FWM in silicon waveguide [8] have been proposed. However, these methods have problems for practical application. They require additional bandwidth reserved for the generated idler light and phase-locking mechanism between signal and pump lights in the FWM process. In addition, the amplitude shift keying (ASK) format is not commonly used in optical communication. In this paper, therefore, we propose a method of all-optical modulation format conversion from OOK and QPSK to 8QAM using nonlinear optical effects in a semiconductor optical amplifier (SOA). Since this method uses XPM and cross gain modulation (XGM) for nonlinear optical effects, it has the advantage that the reserved bandwidth and the phase-locking mechanism are not required. This method is expected to be used for modulation format adaptation because OOK and QPSK formats are well used in optical communication.

As the opposite direction, high-order to low-order modulation format conversion technique is suitable when signals transmitted over long distances are redirected to a short distance or local transmission [9]. For instance, modulation format conversion method from 16QAM to QPSK using optical phase quantizers based on phase sensitive amplifiers [10] and QPSK to BPSK using FWM and pulse width compression [11] have been reported. Quadrature decomposition of a 16QAM signal into two 4 pulse amplitude modulation (PAM) signals has been reported by using idler generation and polarization beam splitters [12], and nonlinear wave mixing [13]. To the best of our knowledge, the conversion from 8QAM to QPSK has not been reported yet. Therefore, in this paper, we also propose an all-optical format conversion method from 8QAM to QPSK and OOK. The proposed system configuration includes SOA [14] and optical threshold device [15]. The SOA is used to impose self-phase modulation (SPM) and gain saturation to the signal.

This paper consists of 4 sections. Section II describes the operation principle of the proposed format conversion from OOK and QPSK to 8QAM and its reversed conversion. Section III describes the proposed system configuration and numerical

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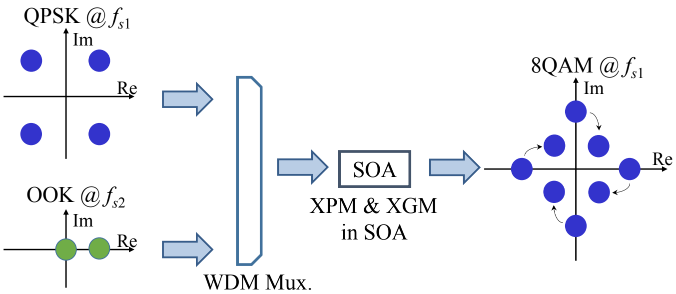

Fig. 1. Schematic diagram of QPSK and OOK to 8QAM conversion using XPM and XGM in SOA.

simulation results measured by bit-error rate (BER) and error vector magnitude (EVM). Conversion system performances are evaluated by dependence of optical signal-to-noise ratio (OSNR), signal power and accumulated chromatic dispersion (CD). Section IV concludes the paper.

II. Operation principle

The schematic diagram of the proposed method from QPSK and OOK to 8QAM conversion is illustrated in Fig. 1. The frequency of the original QPSK signal and OOK signal are f_{s1} and f_{s2}, respectively. These two signals are multiplexed by wavelength division multiplexing (WDM) combiner, then fed into a single SOA. XPM and XGM effects are taken place in the SOA. The phase of the QPSK signal is rotated by XPM and the amplitude of the QPSK signal is relatively attenuated by XGM when the mark pulse of OOK signal propagates at the same time in the SOA. As a result, inner side constellation points of 8QAM format are obtained. The outer side constellation points of 8QAM format are obtained when the phase and amplitude of the QPSK signal are maintained as they are by the OOK space pulse propagation. Modulation format conversion from OOK and QPSK to 8QAM at frequency f_{s1} is achieved in this way. Note that the timing of incoming OOK and QPSK pulses should be aligned to convert to 8QAM pulse. This is achieved by, for example, once detecting the pulse position of QPSK signal and performing re-timing [16] or applying temporal delay [17] for OOK signal.

The schematic diagram of the proposed method from 8QAM to QPSK and OOK conversion is illustrated in Fig. 2. The original 8QAM signal is divided into two. One of the divided 8QAM signal is converted to OOK signal using optical threshold device. The other is converted to QPSK signal by using an SOA. Conversion from 8QAM to QPSK is achieved by using SPM and gain saturation in the SOA. The outer side constellation points of 8QAM format have greater amount of nonlinear phase rotation compared to the inner side constellation points due to SPM. Simultaneously, the amplitude of the outer side and inner side constellation points are amplified and converged to the similar level due to gain saturation. In this manner, the phase and amplitude of the inner and outer side constellation points of the 8QAM format converge to the same positions when the signal has proper power. The conversion from 8QAM to OOK is achieved using optical threshold device [15] by setting the threshold value between the outer side and the inner side constellation points of the 8QAM format. The threshold device distinguishes low and high power levels by using nonlinear ring resonators whose resonant condition changes due to the nonlinear phase change by SPM in a high signal power. Such different power transfer characteristics in low and high power levels enable a threshold function. The low-level or high-level output is obtained when the amplitude of the 8QAM signal is weaker or stronger than the threshold value, respectively. The conversion from 8QAM to OOK is achieved in this way.

Gain saturation in SOA used for the conversion principle is given by the following equation [18]. In SOA, the light amplification phenomenon occurs as a result of the interaction between the carrier density of the conductor and the light. The amplification operation is described by simultaneous equations relating to carrier density and light intensity. It is assumed that the light incident on the amplifier propagates in the z direction while increasing the light intensity by stimulated emission. The light intensity change in the minute section Δz is formally expressed as follows:

$$I(z_0 + \Delta z) = I(z_0) \exp\left[\frac{g_0}{1 + I/I_s}\Delta z\right], \tag{1}$$

$$g_0 = \frac{\tau_c A_g J}{ved}, \tag{2}$$

$$I_s = \frac{h\nu}{\tau_c A_g}, \tag{3}$$

where v is the speed of light in medium, J is the injection current density, e is the electrical charge, d is the active layer width, A_g is the differential gain coefficient, I is the the light intensity in the active layer, $h\nu$ is the energy of one photon, τ_c is the carrier relaxation time. The expression (1) indicates that

$$Gain\ factor\ in\ local\ field = \frac{g_0}{1 + I/I_s}. \tag{4}$$

Equation (4) shows that the gain coefficient depends on light intensity. The gain saturation coefficient when the light intensity is sufficiently small is g_0, and becomes smaller than g_0 as the light intensity increases. For this reason, the amplification gain is constant in the operation region where the input light intensity is small, and decreases as the input light intensity increases.

Further, the nonlinear phase change caused by the change in the refractive index due to the carrier density in the SOA is expressed by the following equation [19]

$$\phi_i = \frac{\pi \Delta L \Gamma g_{m_i}}{2a\lambda} \Delta \overline{n}_N, \tag{5}$$

where ΔL is the length of minute section, Γ is the confinement factor, a is the material gain constant, λ is the peak of the gain wavelength, g_m is the material gain, i is the small section number, $\Delta \overline{n}_N$ is the rate of change of the refractive index in the active region with respect to the carrier concentration.

III. Numerical simulation

A. QPSK and OOK to 8QAM conversion

The numerical simulation setup of QPSK and OOK to 8QAM conversion using OptiSystem (Optiwave Systems Inc.)

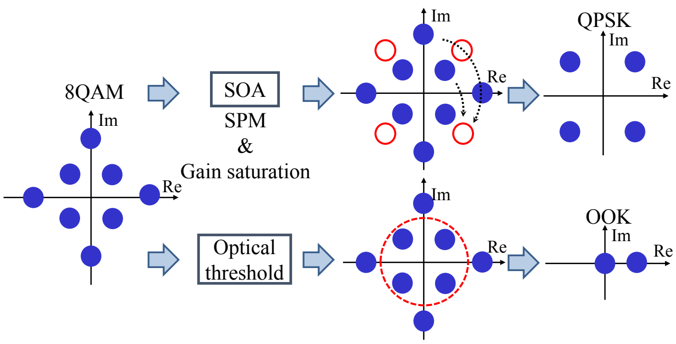

Fig. 2. Schematic of 8QAM to QPSK and OOK conversion using SPM and gain saturation in SOA and optical threshold device.

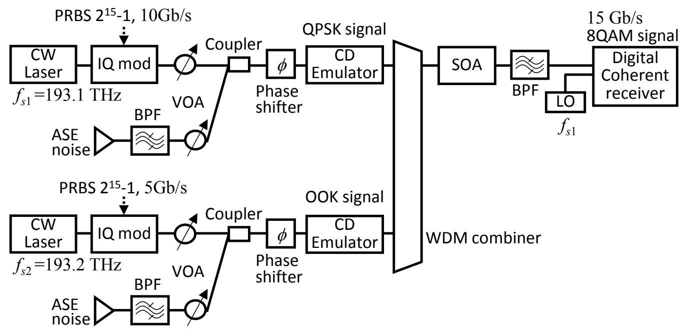

Fig. 3. Numerical simulation setup of QPSK and OOK to 8QAM conversion.

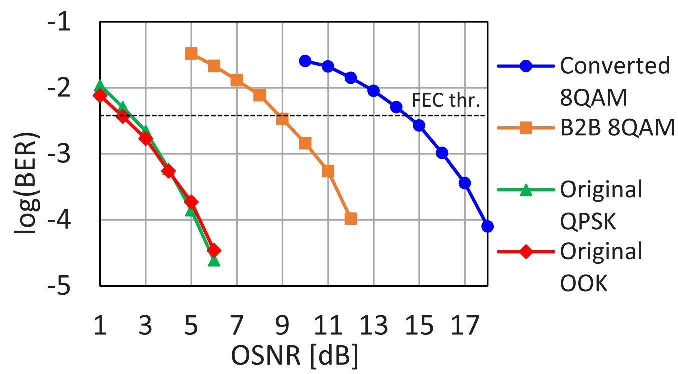

Fig. 4. BER as a function of OSNR in QPSK and OOK to 8QAM conversion. BER of the converted 8QAM is below the FEC threshold when OSNR exceeds 14.5 dB.

is illustrated in Fig. 3 [20]. The original 10-Gbps RZ-QPSK signal at frequency f_{s1}=193.1 THz is generated by CW laser source with zero linewidth and an IQ modulator with $2^{15}-1$ pseudo random bit sequence (PRBS). The original 5-Gbps RZ-OOK signal at frequency f_{s2}=193.2 THz is generated by CW laser source with zero linewidth and another IQ modulator with $2^{15}-1$ PRBS. The reason of the zero linewidth is to avoid signal quality degradation by linewidth enhancement in the SOA. The power of the original QPSK and OOK signals are -3 dBm and -0.5 dBm, respectively. Amplified spontaneous emission (ASE) noise is added to the original QPSK and OOK signals to change OSNR. A CD emulator assuming the dispersion coefficient of 17 ps/nm/km and the dispersion slope of 0.075 ps/nm^2/km at f_{s1} without fiber loss is placed before the WDM combiner. The QPSK and OOK signals are injected into the SOA whose parameters are set as [14] to impose XPM and XGM. The converted 8QAM signal is coherently detected and digitally processed, then bit errors are directly counted. Performed digital processing is enumerated as direct current (DC) blocking, normalization, low-pass filtering, adaptive equalization, and carrier phase recovery. Frequency offset estimation is not performed since the laser linewidth is set as zero. The bit-error rate calculation needs a special consideration since the mapping of 3 bit on each of the converted 8QAM symbol is not in the ordinary Gray-code. The first bit of the 3-bit mapping is 0 and 1 for inner and outer QPSK constellations, respectively. The latter two bits correspond to the ordinary Gray-code mapping for QPSK constellation. This mapping is caused by the usage of original PRBS, namely, the first bit of every 3-bit sequence is used for data of OOK signal and latter two bits are used for data of QPSK signal with ordinary Gray-code mapping.

BER as a function of OSNR in QPSK and OOK to 8QAM conversion is illustrated in Fig. 4. The BER of the converted 8QAM signal is below the dashed line which means 7%-overhead hard decision forward error correction (HD-FEC) threshold of $\log_{10}(3.8\times10^{-3})=-2.42$ when OSNR exceeds 14.5 dB. This result shows that the error free format conversion can be achieved. Moreover, BERs of the original QPSK signal, original OOK signal, and a back-to-back (B2B) 8QAM signal are shown in Fig. 4. The BER curves of the original QPSK and OOK signals have almost 0.5-dB additional OSNR penalty compared to the theoretical value [21]. There are 5.5-dB and 12-dB OSNR penalties on the FEC threshold in between the converted 8QAM signal and B2B 8QAM signal, original QPSK signal, respectively. The main reason of the 5.5-dB OSNR penalty between the B2B and the converted 8QAM is the ASE noise accumulation before performing the format conversion. The accumulated noise affects the signal quality in the nonlinear process in the SOA. Therefore, such a quality degradation can be overcome by reducing the noise accumulation before format conversion as much as possible.

Constellation diagrams of the converted 8QAM signal and the original QPSK signal at OSNR of 15 dB, 18 dB and without noise are illustrated in Fig. 5. Although the constellation points are expected to spread due to the noise accumulation in the SOA, it can be seen that the amplitude of the inner side constellation points of the 8QAM signal much converges compared to the outer side constellation points by the XGM effect in the SOA. Furthermore, outer side constellation points of 8QAM signal spread in the rotation direction compared to the inner side constellation points due to the high-instantaneous power-induced nonlinear phase rotation.

EVM as a function of OOK signal power changed from -8.5 to 7.5 dBm is illustrated in Fig. 6. The QSPK signal power is -3 dBm. OSNR of OOK and QPSK is set to 18 dB. A dashed line on 19.0% EVM means the same FEC threshold [22]. It can be seen that EVM exceeds the threshold when the OOK signal power increases higher than 1.0 dBm, meaning that proper 8QAM format is not obtained. This is because the phase of the QPSK signal is rotated beyond the ideal constellation point due to the stronger XPM caused

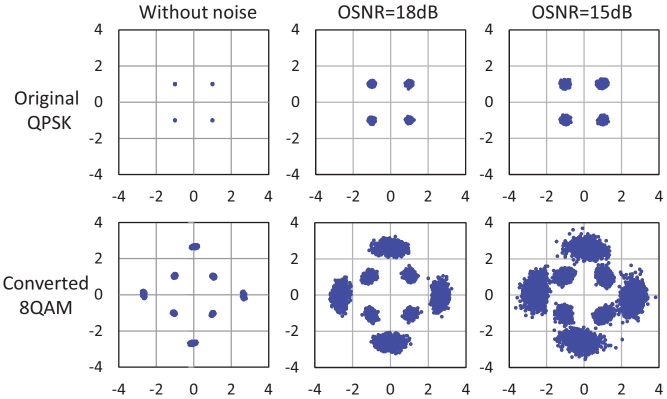

Fig. 5. Constellation diagrams of the converted 8QAM signal and the original QPSK signal without noise, OSNR at 18 dB and 15 dB.

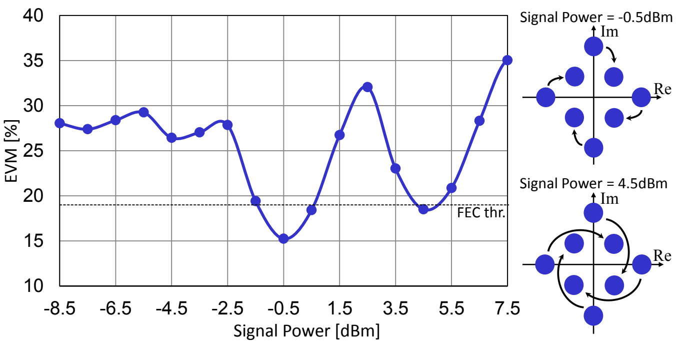

Fig. 6. EVM as a function of OOK signal power. EVM is below the threshold around -0.5 and 4.5 dBm as shown in the right-side constellation schematic.

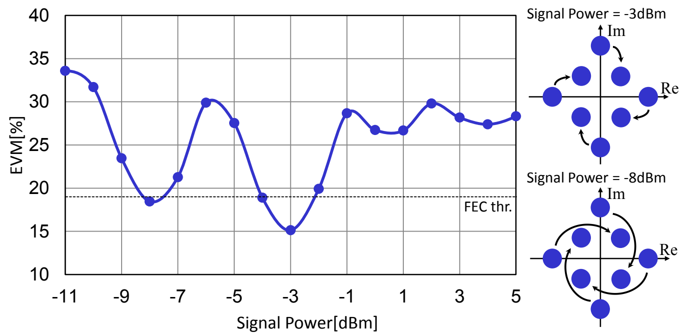

Fig. 7. EVM as a function of QPSK signal power. EVM is below the threshold around -3.0 and -8.0 dBm as shown in the right-side constellation schematic.

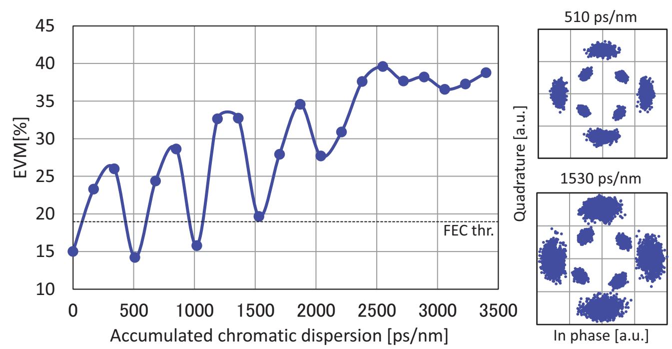

Fig. 8. EVM as a function accumulated CD in OOK, QPSK and constellation diagrams. EVM exceeds the threshold over 1500 ps/nm due to the temporal misalignment and improper instantaneous power of the OOK and QPSK signals due to the accumulated CD.

by higher OOK signal power. Similarly, EVM exceeds the threshold when the OOK signal power is less than -1.5 dBm. This is because the phase of the QPSK signal is not rotated sufficiently due to the weak XPM caused by lower OOK signal power. Note that EVM becomes the 2nd minimum value when the OOK signal power is 4.5 dBm. Even in the stronger XPM situation, the phase of the QPSK signal is rotated by 135 degrees as shown in the right-side schematic, resulted in similar constellation diagram as in the ideal 45 degree rotation. Therefore, the EVM shows lower value at that power.

EVM as a function of QPSK signal power changed from -11 to 5 dBm is illustrated in Fig. 7. The OOK signal power is -0.5 dBm. OSNR of OOK and QPSK is set to 18 dB. It can be seen that EVM exceeds the threshold when the QPSK signal power is higher than -2 dBm, meaning that proper 8QAM format is not obtained. This is because the OOK power decreases due to the gain saturation effect in the SOA, so the phase rotation on the QPSK signal by XPM is not sufficient. EVM again exceeds the threshold when the QPSK power is less than -4 dBm. This is because the OOK power increases by the gain saturation, so the phase rotation on the QPSK signal by XPM is too strong. EVM becomes the 2nd minimum value when the OOK signal power is -8 dBm. The reason is the same as in the OOK signal power of the 4.5 dBm in Fig. 6.

EVM as a function of CD accumulated in OOK and QPSK signals before format conversion is illustrated in Fig. 8. The accumulated CD is emulated by changing its fiber length from 0 km to 200 km, and the OSNR is set to 18 dB. It can be seen that the calculated EVM exceeds the FEC threshold over 1500 ps/nm. There are also some points that exceed the FEC threshold at CD less than 1500 ps/nm. This is because the proper 8QAM format cannot be obtained due to the temporal misalignment of the QPSK and OOK pulses by the influence of the CD. Constellation diagrams of the converted 8QAM at CD of 510 ps/nm and 1530 ps/nm are also plotted.

Eye diagrams of the 8QAM signal at CD of 510 ps/nm and 1530 ps/nm are illustrated in Fig. 9. The eye diagram at CD of 1530 ps/nm fluctuates than that of 510 ps/nm due to the loss-less CD emulation and reduction of gain saturation in the SOA. Therefore, it is found that the outer side constellations of the 8QAM signal at CD of 1530 ps/nm in Fig. 8 much spread compared to CD of 510 ps/nm.

B. 8QAM to QPSK and OOK conversion

Numerical simulation setup of 8QAM to QPSK and OOK conversion using OptiSystem is illustrated in Fig. 10 [23]. The original 15-Gbps 8QAM signal at frequency f_{s3}=193.1 THz is generated by CW laser source with zero linewidth and an IQ modulator with $2^{15}-1$ PRBS. The power of original 8QAM signal is -4.9 dBm. ASE noise is added to the original 8QAM signal to change OSNR. A CD emulator assuming the dispersion coefficient of 17 ps/nm/km and the dispersion slope of 0.075 ps/nm^2/km at f_{s1} without fiber loss is placed before

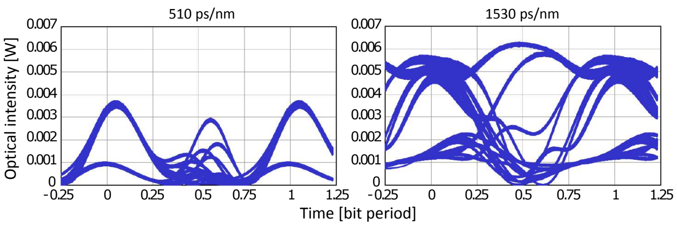

Fig. 9. Eye diagrams of the converted 8QAM at CD of 510 ps/nm and 1530 ps/nm. Optical intensity of CD of 1530 ps/nm fluctuates due to the loss-less CD emulation and reduction of gain saturation in the SOA.

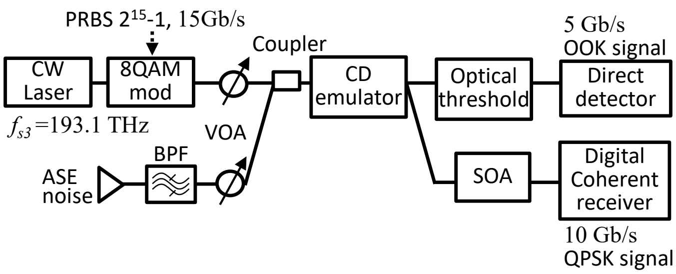

Fig. 10. Numerical simulation setup of 8QAM to QPSK and OOK.

the optical threshold device and SOA. The SOA parameters are set as [14]. The converted QPSK signal is coherently detected and digitally processed, and the converted OOK signal is directly detected. Bit errors are directly counted.

BER as a function of OSNR in 8QAM to QPSK and OOK conversion is illustrated in Fig. 11. The meaning of BER curve of the converted QPSK and OOK (blue diamond legend) is that the number of bit error of the demodulated OOK data and QPSK data are added and it is divided by the total number of transmitted PRBS. The BER of the converted QPSK and OOK is below the HD-FEC threshold when OSNR exceeds 14.0 dB. This result shows that the error free format conversion can be achieved. Moreover, BERs of the converted QPSK signal, original 8QAM and the converted OOK signal are shown in Fig. 11. It is found that there is an OSNR penalty of 2 dB on the FEC threshold between original 8QAM signal and converted QPSK and OOK signal due to the ASE noise accumulation before performing format conversion.

Constellation diagrams of the original 8QAM signal and the converted QPSK signal at OSNR of 14 dB, 18 dB and without noise are illustrated in Fig. 12. In the constellation diagram of the QPSK signal after conversion, it can be seen that the constellation points spread in the rotation direction compared to the original 8QAM. This is due to the effect of nonlinear phase rotation by SPM.

BER as a function of 8QAM signal power changed from -10 to 0 dBm is illustrated in Fig. 13. OSNR of 8QAM is set to 18 dB. It is found that there is no point exceeding the FEC threshold. The threshold value of the optical threshold device is changed according to the 8QAM signal power. Thus, even if the 8QAM signal power is changed, conversion from 8QAM to OOK becomes error free. Consider conversion from 8QAM to QPSK, the range of the input signal power in Fig. 13 is in the gain saturation regime of the SOA. Therefore, the 8QAM signal power converges to a similar value and then the

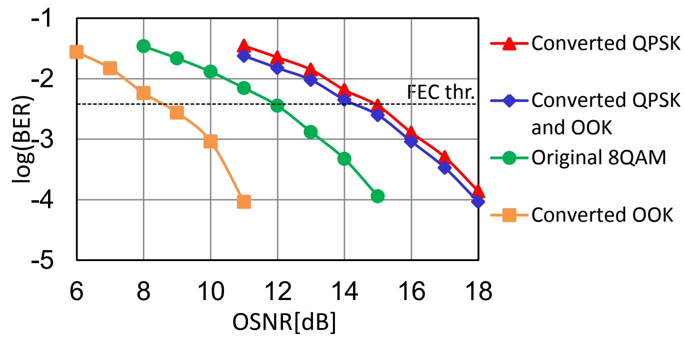

Fig. 11. BER as a function of OSNR in 8QAM to QPSK and OOK. BER of the converted QPSK and OOK is below the FEC threshold when OSNR exceeds 14.0 dB.

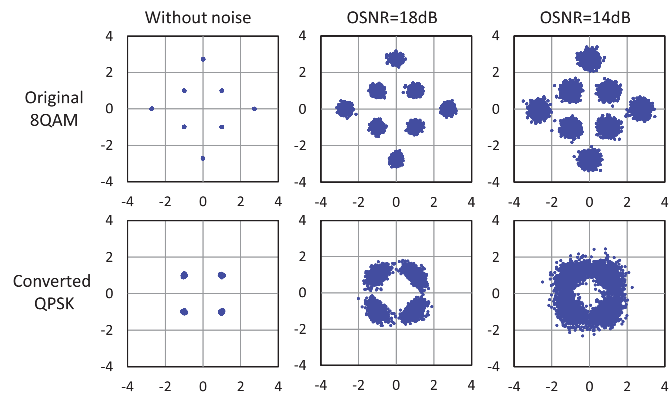

Fig. 12. Constellation diagrams of the original 8QAM signal and the converted QPSK signal without noise, OSNR at 18 dB and 14 dB.

similar phase rotation is imposed by SPM. QPSK format can be obtained regardless of 8QAM signal power.

BER of the converted QPSK and OOK as a function of accumulated CD in 8QAM signal is illustrated in Fig. 14. The accumulated CD is emulated by changing the fiber length of the CD emulator from 0 km to 150 km, and the OSNR is set to 18 dB. It is found that the calculated BER exceeds the FEC threshold over 2200 ps/nm. This is because the proper QPSK format cannot be obtained since 8QAM pulse waveform is distorted by the influence of the CD. Constellation diagrams of the original 8QAM signal and the converted QPSK signal at CD of 170 ps/nm and 2040 ps/nm are also shown. It is observed that the constellation points of the original 8QAM signal at the CD of 2040 ps/nm shrinks and the distance between adjacent points decreases by the CD compared to the CD of 170 ps/nm. Therefore, the converted QPSK at the CD of 2040 ps/nm becomes less tolerate to the nonlinear phase rotation.

IV. Conclusion

We have proposed the all-optical modulation format conversion systems between OOK, QPSK and 8QAM. From OOK and QPSK to 8QAM conversion was achieved by using XPM and XGM in SOA. Advantage of this conversion system is that the reserved bandwidth and the phase-locking are not required. Furthermore, it is expected to be applied to practical use for modulation format adaptation since the original formats of

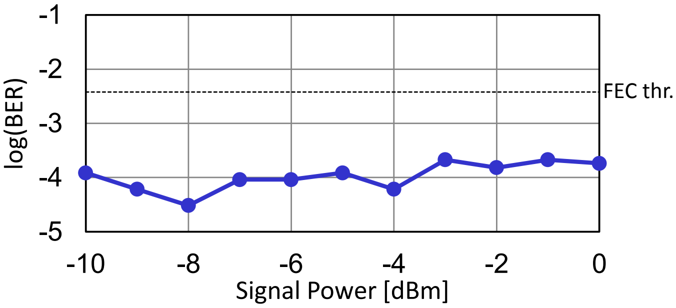

Fig. 13. BER as a function of 8QAM signal power. There is no point exceeding the FEC threshold in this range.

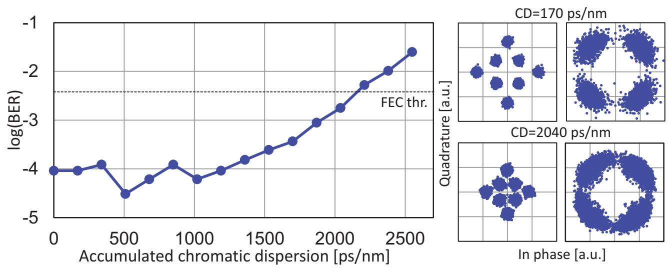

Fig. 14. BER as a function of accumulated CD in 8QAM and constellation diagrams. BER exceeds the FEC threshold over 2200 ps/nm since the proper QPSK format cannot be obtained since 8QAM pulse waveform is distorted by CD.

OOK and QPSK are well used for optical communications. The conversion performance was evaluated by numerical simulation. As a result, it was found that the proposed method showed 5.5-dB OSNR penalty between the B2B 8QAM signal on FEC threshold, and depended on the signal strength before conversion and the accumulated CD. It was also revealed that the strict power adjustment and temporal alignment of QPSK and OOK pulses were required.

From 8QAM to QPSK and OOK conversion was achieved by SPM and gain saturation in SOA, and by using an optical threshold device. As a result of numerical simulation, it was found that the proposed method showed 2-dB OSNR penalty to that of the original 8QAM signal on FEC threshold and depended on the accumulated CD. As a future work, we will consider experimental verification of format conversion of this study.

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