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Suppression of large error floor in 1024 QAM digital coherent transmission by compensating for GAWBS phase noise

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Abstract: There is a large error floor in an ultra multi-level digital coherent transmission signal of 1024 QAM or higher, and we have yet to determine its origin. In this paper, we show that this large error floor results from guided acoustic-wave Brillouin scattering (GAWBS) phase noise. We prove experimentally that such an error floor can be greatly reduced by compensating for the GAWBS noise with a phase modulation technique. We show that the BER of a 1024 QAM signal was reduced from 8.7×10^{-4} to 2.7×10^{-4} after a 160 km transmission with GAWBS noise compensation. Furthermore, we successfully extend the transmission distance from 160 to 240 km with a 7% overhead forward error correction.

1. Introduction

Higher-order quadrature amplitude modulation (QAM) transmission has been intensively studied to meet the growing demand for higher transmission capacity in optical backbone networks and data centers [1–2]. Recently, a polarization-multiplexed 4096 QAM transmission, which is currently the highest multiplicity obtained in a coherent optical transmission, has been demonstrated over 160 km with a potential spectral efficiency (SE) of 15.8 bit/s/Hz [3]. Probabilistically shaped 4096 QAM transmissions have also been reported that improve the system power margin and SE [4–5]. In such ultra-high multilevel QAM transmissions, the phase error tolerance becomes small, which causes a large error floor in the BER performance and limits the transmission distance.

On the other hand, it has been pointed out that guided acoustic-wave Brillouin scattering (GAWBS) noise impairs QAM digital coherent transmission [6–7]. GAWBS is an optical phase fluctuation caused by the interaction between a lightwave and thermally excited acoustic modes in a transmission fiber [8–9]. GAWBS is not dependent on input power, and the amount of phase noise that is generated is proportional to the fiber length. To solve this problem, several GAWBS noise compensation schemes have been demonstrated with 64 QAM transmissions [6].

In this paper, we detail our realization of GAWBS noise compensation in a polarization-multiplexed 1024 QAM transmission [10]. We analyzed the bit error rate (BER) performance of a 1024 QAM signal after a 160 km transmission, and then showed that GAWBS phase noise was a major factor causing a large error floor. By using a phase modulation method [6], the error floor, excluding the amplified spontaneous emission (ASE) noise, was successfully reduced by 37%, and the BER was reduced from 8.7×10^{-4} to 2.7×10^{-4} after a 160 km transmission. Furthermore, the transmission distance was successfully extended from 160 to 240 km with a 7% overhead forward error correction (FEC) by compensating for the GAWBS noise.

2. Principle of GAWBS noise compensation using a phase modulation method

GAWBS has two types of resonance modes, i.e., $R_{0,m}$ modes vibrating only in the radial direction and $TR_{2,m}$ modes vibrating in both the radial and torsional directions. The $R_{0,m}$ modes change

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the refractive index and cause phase noise in the optical signal, while the $TR_{2,m}$ modes change the refractive index along the azimuthal direction and cause not only phase noise but also depolarization due to birefringence. Here, the scattering efficiency of the $R_{0,m}$ modes is generally more dominant (an order of magnitude larger) than that of the $TR_{2,m}$ modes.

Recently, we demonstrated GAWBS phase noise compensation in a digital coherent transmission with three different methods, namely phase modulation, injection locking, and digital compensation [6]. Using these methods, we successfully reduced the error vector magnitude (EVM) of a 64 QAM signal after a 160 km transmission. We pointed out that the existence of GAWBS noise may limit the ultimate performance of a digital coherent system since it occurs in an acoustic vibration in thermal equilibrium in a silica fiber structure. Modulation formats with higher multiplicity levels may suffer greatly from the noise, as a higher multiplicity requires a higher OSNR. Here, we show that although an ultra-high multilevel QAM transmission of, for example, 1024 QAM, has a large power penalty [11], it can be reduced by compensating for the GAWBS noise.

Figure 1 shows an experimental setup for GAWBS noise compensation with a phase modulation method [6]. In the previous work [6], we used CW laser diodes for the transmitter and LO. In this system, on the other hand, we use narrow-linewidth fiber lasers both for the transmitter and LO, in which the phase noise in the coherent detection circuit was reduced by using fiber lasers. Here, the LO output does not include the GAWBS information because the bandwidth of the optical phase-locked loop (OPLL) circuit [12] was only several MHz. The GAWBS information can be extracted with a double balanced mixer (DBM) and then fed back to the phase modulator under a reverse phase condition [6]. To adjust the timing between the GAWBS noise and the transmitted signal, an optical delay line was installed in front of the phase modulator. By using the phase modulation method, we can in principle cancel the GAWBS noise in a transmitted signal.

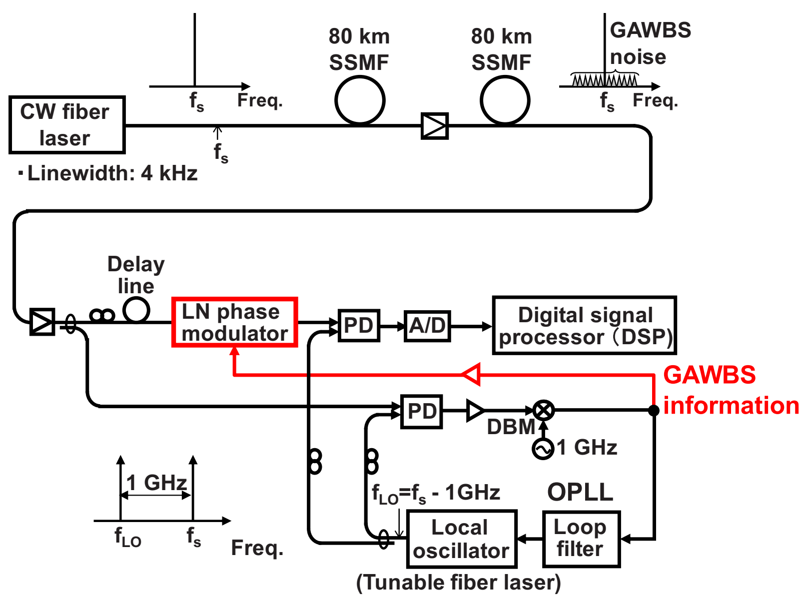

Fig. 1. Experimental setup for GAWBS noise compensation with a phase modulation method.

Figures 2(a) and 2(b), respectively, show the constellations of a carrier signal after a 160 km transmission without and with the use of a phase modulation method. The phase noise without GAWBS noise compensation was ± 1.24 degrees as shown in Fig. 2(a), which was larger than the angle of 0.95 degrees between adjacent symbols in the 1024 QAM format. This indicates that the GAWBS noise may cause serious bit errors in such a high multiplicity QAM transmission. By employing the phase modulation method, the phase noise was reduced to ± 0.52 degrees as shown in Fig. 2(b).

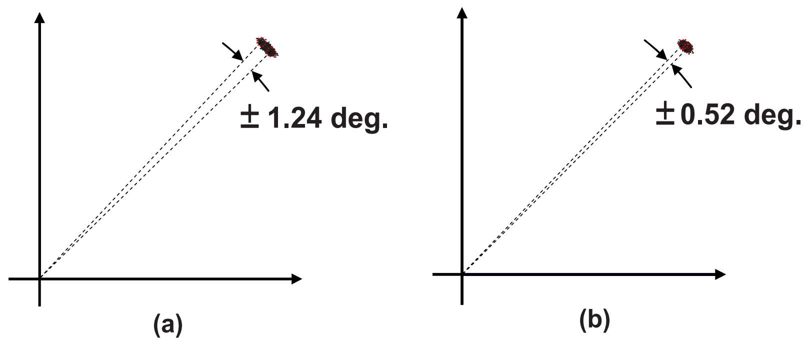

Fig. 2. Constellations of a carrier signal after a 160 km transmission. (a) Without GAWBS noise compensation and (b) with GAWBS noise compensation.

3. Application of the GAWBS noise compensation technique to a polarization-multiplexed 1024 QAM digital coherent transmission

Figure 3 shows our experimental setup for a polarization-multiplexed 1024 QAM transmission, in which we incorporated the phase modulation method described in section 2. A polarization-multiplexed signal mainly suffers from GAWBS phase noise caused by $R_{0,m}$ modes, which is independent on the polarization state of the signal. Therefore, we can compensate for the phase noise on the two orthogonal polarization data simultaneously by using a common feedback circuit with the phase modulation method. We used a pilot tone signal, whose frequency was downshifted by 10 GHz against the carrier frequency of the QAM signal, to detect the GAWBS noise. A polarization-multiplexed 3 Gbaud, 1024 QAM signal and a pilot tone signal were launched into a fiber link composed of 80 km spans of ultra large area (ULA) fiber, whose loss and effective core area were 0.18 dB/km and 153 μm^2, respectively. Here, for experimental simplicity, we set the power of the pilot tone t so that it was equal to that of the QAM signal. At the receiver, the transmitted QAM and pilot tone signals were individually extracted by using a fiber splitter and two optical bandpass filters. The extracted pilot tone signal was coupled to a photo-detector (PD) to obtain the GAWBS information. On the other hand, the extracted QAM signal was homodyne detected with an LO under OPLL operation. Here, we installed a phase modulator for GAWBS compensation in the LO signal path since the modulator cannot be applied to a polarization-multiplexed QAM signal. The GAWBS information was modulated on the LO signal under an in-phase condition, and then the GAWBS noise in the QAM signal was removed by homodyne detection with the modulated LO. Here, the fiber length of the delay line was less than 10 m, and the GAWBS induced in the delay line can be ignored. The homodyne detected QAM data were A/D converted and processed offline with a digital signal processor (DSP). In the DSP, the QAM data were polarization demultiplexed with the Stokes vector method [13]. Then, digital back-propagation (DBP) [14] and frequency domain equalization [15], respectively, were employed to compensate for the nonlinear phase rotation and waveform distortion that occurred during the transmission.

Figures 4(a) and 4(b) show constellations of X- and Y-polarization data after a 160 km transmission without and with GAWBS noise compensation, respectively. By applying the phase modulation method as shown in Fig. 4(b), the phase fluctuations at the four corners were clearly reduced, and the BER was improved from 8.7×10^{-4} to 2.7×10^{-4} for the X-polarization and

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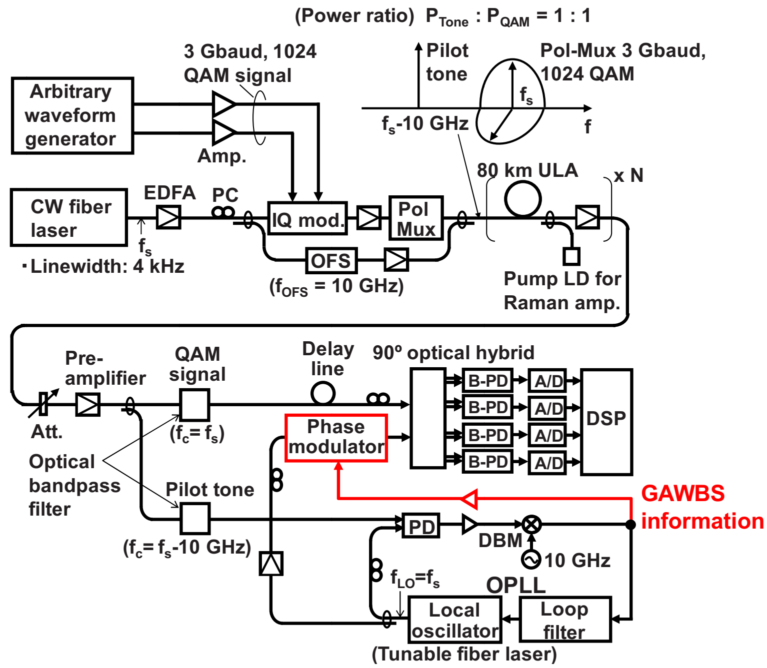

Fig. 3. Experimental setup for polarization-multiplexed, 3 Gbaud, 1024 QAM transmission over a 160 km transmission with a GAWBS noise compensator.

from 9.5×10^{-4} to 3.3×10^{-4} for the Y-polarization. Both polarization data were simultaneously improved with the GAWBS noise compensation.

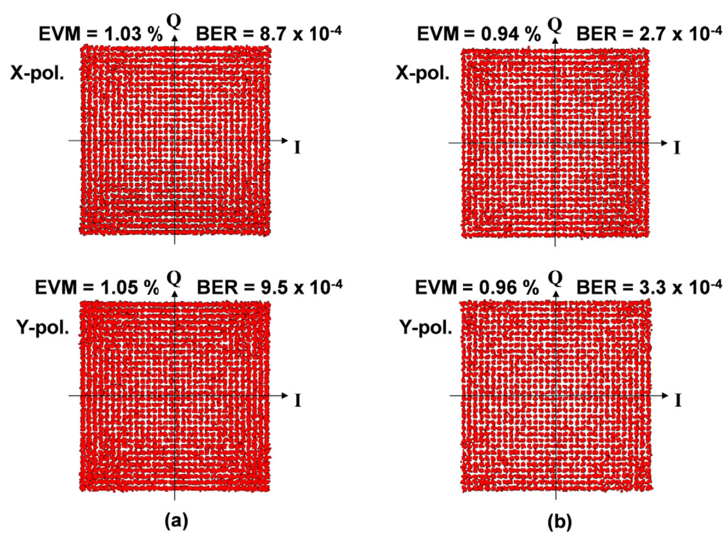

Fig. 4. Constellations of X- and Y-polarization data after a 160 km transmission. (a) Without GAWBS noise compensation and (b) with GAWBS noise compensation.

Figure 5 shows the BER performance of X- and Y-polarization data as a function of the launched power after a 160 km transmission without and with GAWBS noise compensation, respectively. Here, the launched power was not changed before and after compensation since the

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GAWBS noise is not related to the launched power. We set the fiber launched power at 3 dBm to maximize the OSNR and minimize nonlinear impairments. Figure 6 shows an RF spectrum of the homodyne-detection signal after a 160 km transmission obtained with the optimum launched power. The signal to noise ratio (SNR) of the signal was 44.2 dB. Note here that the GAWBS noise pervades the QAM spectrum because all data spectra suffer from GAWBS noise with an acoustic mode bandwidth of about 500 MHz [6]. The spectral broadening at the band edges of the QAM spectrum is not GAWBS noise, rather it is due to the nonlinear phase modulation that occurs during transmission.

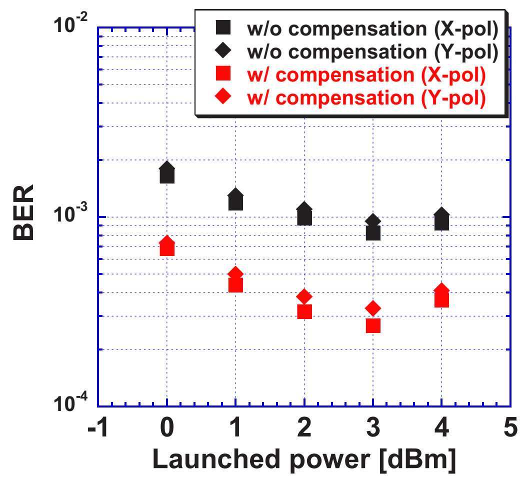

Fig. 5. BER performance of X- and Y-polarization data after 160 km transmission as a function of fiber launched power.

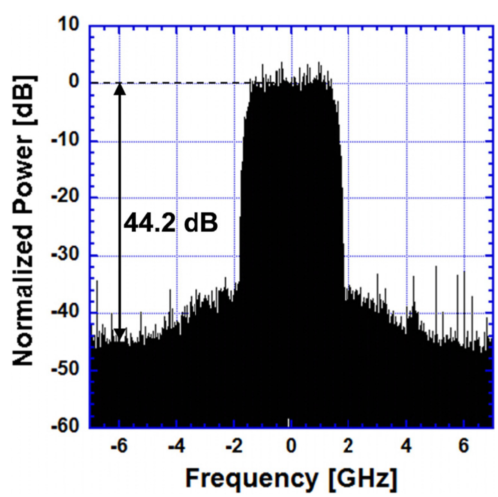

Fig. 6. RF spectrum of demodulated QAM signal after 160 km transmission with a launched power of 3 dBm.

4. Analysis of SNR improvement in error floor suppression

Figure 7 shows the BER performance of a 1024 QAM signal after a 160 km transmission as a function of the SNR. Here, the SNR of the QAM signal was changed by using a variable attenuator in front of a pre-amplifier, which is an EDFA operating in an automatic gain control mode. The black, blue and red plots show the BER under a back-to-back condition, and after a 160 km transmission without and with GAWBS noise compensation, respectively. Without GAWBS noise compensation, the BER values at the SNR of more than 42 dB were floored by around 1×10^{-3} after a 160 km transmission. On the other hand, after GAWBS noise compensation, the SNR penalty at an FEC threshold BER of 2×10^{-3} was reduced by 2.2 dB and the BER at the maximum SNR of 44.2 dB was decreased from 8.7×10^{-4} to 2.7×10^{-4}. This result indicates that the GAWBS noise caused the error floor and that GAWBS noise compensation plays a very important role in improving the transmission quality of such a high multilevel QAM transmission.

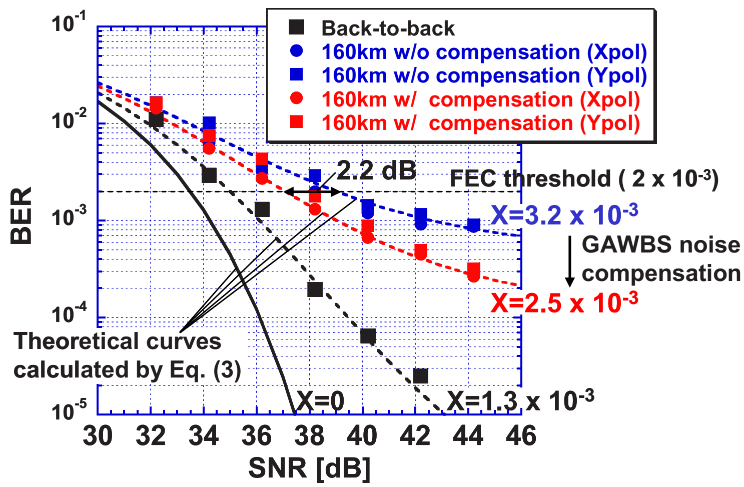

Fig. 7. BER performance of a 1024 QAM signal after a 160 km transmission as a function of SNR. The solid and broken lines are theoretical curves calculated by using Eq. (3) with different X values.

Next, we consider the cause of the bit error quantitatively. If there is no additional noise expect for the ASE noise, the SNR of the QAM signal is given by

$$SNR = P_S / P_{ASE}, \tag{1}$$

where P_S and P_{ASE} are the power of the QAM signal and the power of the ASE noise, respectively. However, there is some additional noise including the waveform distortion caused by device imperfections, nonlinear impairments, and the GAWBS noise. The actual SNR including the additional noise, P_{add}, is given by

$$SNR^* = \frac{P_S}{P_{ASE} + P_{add}} = \frac{1}{1/SNR + X}. \tag{2}$$

Here, X is the additional noise power to signal power ratio of P_{add}/P_S. The theoretical BER against the actual $SNR*$ is given by the following equation for 1024 QAM transmission [2].

$$BER = \frac{31}{160} erfc \sqrt{\frac{SNR^*}{682}} \tag{3}$$

The solid and broken lines in Fig. 7 show theoretical curves calculated by Eq. (3) for $X = 0$ and fitted X values, respectively. The fitted X value for back-to-back was 1.3×10^{-3}, which corresponds to the waveform distortion caused by imperfections in the transmission system devices and the quantization noise in the A/D converter. On the other hand, the fitted X values for a 160 km transmission without and with GAWBS noise compensation were changed to 3.2×10^{-3} and 2.5×10^{-3}, respectively. The additional noise increased by 1.9×10^{-3} during the fiber transmission, and it was reduced by 0.7×10^{-3} (37%) with GAWBS noise compensation. The residual noise of 1.2×10^{-3} may be mainly caused by nonlinear phase rotation, which was not completely compensated for by DSP. To further improve the BER performance, the resolution of the A/D converter should be increased as this will improve the compensation performance for nonlinear distortion with the DBP method [16].

Figure 8 shows BER performance as a function of transmission distance. Here, BER values were counted from 40960 symbol data. By applying the phase modulation method, the transmission distance was successfully increased to 240 km with a 7% overhead FEC.

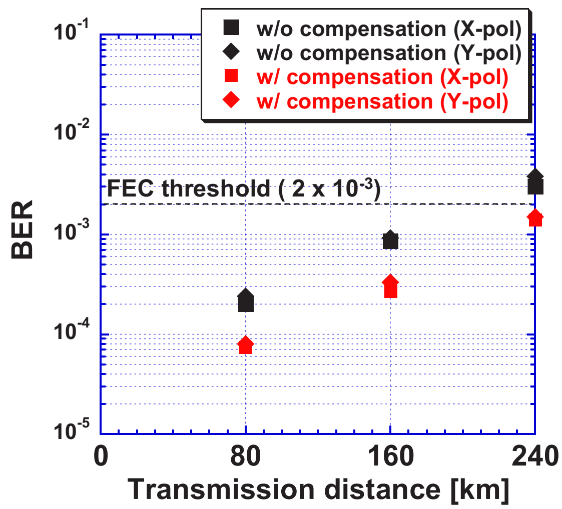

Fig. 8. BER performance of a 1024 QAM signal as a function of transmission distance.

In the present single channel transmission system, for experimental simplicity we used a bandwidth of 8.2 GHz to set the tone signal for GAWBS detection. As a result, the spectral efficiency was 4.8 bit/s/Hz. However, in a WDM transmission, only one tone signal is needed for GAWBS noise detection as shown in Fig. 9 since the GAWBS noise characteristics do not depend on the signal wavelength. As a result, the bandwidth of the WDM signal (several THz) is much larger than that of the guard band for the one tone signal (1~10 GHz). Therefore, the decrease in SE for GAWBS noise compensation is negligible. Thus, we can greatly improve the performance of a multilevel WDM coherent transmission.

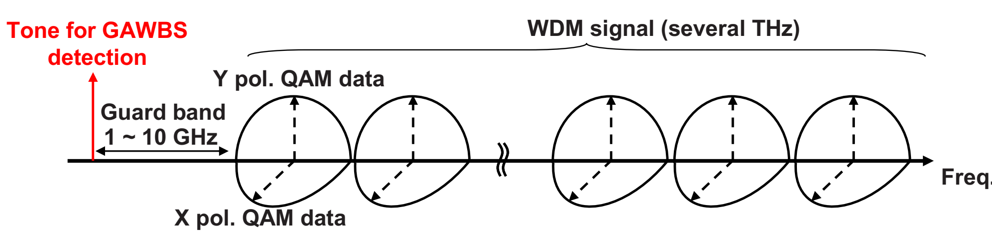

Fig. 9. Spectral layout of a WDM transmission system with GAWBS noise compensation.

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5. Conclusion

We demonstrated GAWBS noise compensation in a polarization-multiplexed 1024 QAM transmission by using a phase modulation method. After a 160 km transmission, the total noise floor was reduced by 37% with GAWBS noise compensation, and the BER was improved from 8.7×10^{-4} to 2.7×10^{-4}. Furthermore, the transmission distance was successfully increased to 240 km with the present scheme. We proved that GAWBS noise compensation is a very effective way of improving the transmission quality of ultra-multilevel QAM transmissions.

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Disclosures

The authors declare no conflicts of interest.

References

1. M. Nakazawa, K. Kikuchi, and T. Miyazaki, eds., *High Spectral Density Optical Transmission Technologies* (Springer, 2010) Chap. 3.
2. I. P. Kaminow, Tingye Li, and A. E. Willner, eds., *Optical Fiber Telecommunications VIB -Systems and Networks* (Academic, 2013) Chap. 7.
3. M. Terayama, S. Okamoto, M. Yoshida, K. Kasai, and M. Nakazawa, "QAM (72 Gbit/s) single-carrier coherent optical transmission with a potential SE of 15.8 bit/s/Hz in all-Raman amplified 160 km fiber link," in *Optical Fiber Communication Conference* 2018. paper Th1F.2.
4. S. Okamoto, M. Terayama, M. Yoshida, K. Kasai, T. Hirooka, and M. Nakazawa, "Experimental and numerical comparison between probabilistically-shaped 4096 QAM and uniformly-shaped 1024 QAM in all-Raman amplified 160 km transmission," Opt. Express **26**(3), 3535–3543 (2018).
5. S. L. I. Olsson, J. Cho, S. Chandrasekhar, X. Chen, P. J. Winzer, and S. Makovejs, "Probabilistically shaped PDM 2018-QAM transmission over up to 200 km of fiber using standard intradyne detection," Opt. Express **26**(4), 4522–4530 (2018).
6. M. Nakazawa, M. Yoshida, M. Terayama, S. Okamoto, K. Kasai, and T. Hirooka, "Observation of guided acoustic-wave Brillouin scattering noise and its compensation in digital coherent optical fiber transmission," Opt. Express **26**(7), 9165–9181 (2018).
7. M. Nakazawa, M. Terayama, S. Okamoto, M. Yoshida, K. Kasai, and T. Hirooka, "Observation of guided acoustic-wave Brillouin scattering and its digital compensation in coherent QAM transmission," in *Optical Fiber Communication Conference* 2018, paper M4B.2.
8. R. M. Shelby, M. D. Levenson, and P. W. Bayer, "Resolved forward Brillouin scattering in optical fiber," Phys. Rev. Lett. **54**(9), 939–942 (1985).
9. R. M. Shelby, M. D. Levenson, and P. W. Bayer, "Guided acoustic-wave Brillouin scattering," Phys. Rev. B **31**(8), 5244–5252 (1985).
10. M. Yoshida, N. Takefushi, M. Terayama, K. Kasai, T. Hirooka, and M. Nakazawa, "Reverse phase modulation technique for GAWBS noise error floor elimination in 1024 QAM-160 km digital coherent transmission," in *OptoElectronics and Communications Conference* 2018, paper, 4B1-3.
11. Y. Koizumi, K. Toyoda, M. Yoshida, and M. Nakazawa, "QAM (60 Gbit/s) single-carrier coherent optical transmission over 150 km," Opt. Express **20**(11), 12508–12514 (2012). (2012).
12. K. Kasai, J. Hongo, M. Yoshida, and M. Nakazawa, "Optical phase-locked loop for coherent transmission over 500 km using heterodyne detection with fiber lasers," IEICE Electron. Express **4**(3), 77–81 (2007).
13. B. Szanfraniec, B. Nebendahl, and T. Marshall, "Polarization demultiplexing in Stokes space," Opt. Express **18**(17), 17928–17939 (2010).
14. C. Paré, A. Villeneuve, P.-A. Bélanger, and N. J. Doran, "Compensating for dispersion and the nonlinear Kerr effect without phase conjugation," Opt. Lett. **21**(7), 459–461 (1996).
15. Y. Koizumi, K. Toyoda, T. Omiya, M. Yoshida, T. Hirooka, and M. Nakazawa, "512 QAM transmission over 240 km using frequency-domain equalization in a digital coherent receiver," Opt. Express **20**(21), 23383–23389 (2012).
16. T. Omiya, M. Yoshida, and M. Nakazawa, "400 Gbit/s 256 QAM-OFDM transmission over 720 km with a 14 bit/s/Hz spectral efficiency by using high-resolution FDE," Opt. Express **21**(3), 2632–2641 (2013).