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Performance Evaluation of Highly Nonlinear Fiber (HNLF) Based Optical Phase Conjugation (OPC) in Long Haul Transmission of 640 Gbps 16-QAM CO-OFDM

Jingjing Wang , Yongtao Du, Chunhao Liang , Zhong Li and Jing Fang *

Shandong Provincial Engineering and Technical Center of Light Manipulations & Shandong Provincial Key Laboratory of Optics and Photonic Device, School of Physics and Electronics, Shandong Normal University, Jinan 250358, China; wjj@sndu.edu.cn (J.W.); 2018020582@stu.sndu.edu.cn (Y.D.); cliang@dal.ca (C.L.); 107036@sndu.edu.cn (Z.L.)

* Correspondence: fangjing@sndu.edu.cn

Abstract: This paper presents the quantitative measurement through an experimental test of 640 Gbps 16-QAM coherent-optical orthogonal frequency-division multiplexing (CO-OFDM) over 800 km optical fiber with mid-link optical phase conjugation (OPC) using highly nonlinear fiber (HNLF). The first focus is the OPC parameter optimization, including the optimization of HNLF length and signal/pump power that inputs into OPC. Four different HNLFs, as the illustrative examples, are investigated. The second focus is to investigate the effects of fiber dispersion, nonlinearity, and amplified spontaneous emission (ASE) noise on the long-haul transmission of 16-QAM CO-OFDM signal, and the OPC compensation efficiency. The performance evaluation focuses on the conversion efficiency (CE), received signal constellation, Q-factor improvement, and bit error rate (BER) at the receiver end. Such end-to-end performance evaluation is important because the 16-QAM CO-OFDM signal status is heterogeneous and the mitigation of transmission impairments to the signal is still unclear. The OPC parametric optimization is achieved experimentally using commercially available HNLFs with different scenarios and the numerical results are interpreted in conjunction with simulations.

Keywords: 16-QAM CO-OFDM; optical phase conjugation (OPC); four-wave mixing (FWM); high nonlinear fiber (HNLF); OPC parameter



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1. Introduction

The optical network demands to have a transmission capacity of over 1000 Gbps, so coherent-optical orthogonal frequency-division multiplexing (CO-OFDM) as an advanced modulation scheme is currently under investigation to support both high spectral efficiency and long transmission distance. The advantage of CO-OFDM includes seamlessly multiplexed sub-carriers which not only offer a high spectral efficiency but also enable efficient channel estimation and dynamic allocation of carrier number and data rate at negligible hardware cost. In 2016, Ellis et al. demonstrated a single-wavelength 400 Gbps OFDM experimental system [1]. However, due to the relatively high peak-to-average power ratio, the long-haul transmission of CO-OFDM is constrained by self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave-mixing (FWM), which become significant under a high signal launched power [2]. From this point of view, if high launched power is used to improve the optical signal-to-noise ratio (OSNR) and transmission distance, the nonlinear mitigation is indispensable.

There are many approaches of nonlinear compensation available in the literature. Bharath et al. proposed an adaptive modulation technique to mitigate fiber nonlinear effects [3]. Optical phase conjugation (OPC) is an approach for nonlinear compensation in long haul transmission over optical fiber, where the signal formats and bit rates are

heterogeneous and agnostic [4,5]. OPC based on FWM benefits from the uniqueness of signal-transparent, multichannel-adaptive, wide bandwidth, and effective in simultaneous compensation of linear dispersion and nonlinear impairments [6,7]. OPC combined with wavelength division multiplexing (WDM) to transmit intensity-modulated and phase-modulated signals were tested in the laboratory [6]. Likewise, OPC is also utilized in a long-haul transmission based on multichannel and agnostic modulation-format/bitrate operations [7–9]. Recently, CO-OFDM has become increasingly popular owing to its capability to retrieve complex signals [10,11]. Whilst considering long haul transmission, linear dispersion and nonlinear effect in fiber can distort the signal [11,12]. There are a number of digital OPC solutions, including a semiconductor optical amplifier (SOA) [13], periodically-poled lithium-niobate (PPLN)-based guard-band-less optical phase conjugation [14], and silicon waveguide-based OPC [15]. However, such OPC solutions are inefficient for multiple sub-channel operations in real-time due to the limited available bandwidth of the components. Besides, the nonlinear distortion compensation requires a large computing resource.

In practice, mid-link OPC, also named mid-span spectral inversion (MSSI), is utilized to enhance the transmission quality over long haul fiber [1], where the key element for optical phase conjugation is HNLF [2] through XPM and FWM effects. For example, mid-link OPC compensation is employed in $2\times$, $4\times$, and $8\times$ 28 Gbps PM-QPSK over 100 km fiber [8] and $3\times$ 20 Gbps PAM4 over 360 km fiber [9]. The numerical results demonstrate that OPC compensates 90% of the signal nonlinear interference, equivalent to 2.3 dB Q-factor gain [10]. Furthermore, mid-link OPC implemented by wavelength shift-free technique [11] shows that 0.7 dB gain in Q-factor can be obtained in the transmission of $8\times$ 200 Gb/s polarization division multiplexed 16-QAM over 1.6 Tb/s fiber for 800 km. Regarding to WDM employed in long haul fiber transmission, a 64-QAM signal over 400 km is equipped with mid-link OPC [16]. The numerical results show that Q-factor gain up to 2.5 dB can be achieved.

Nonlinear distortion mitigation in OPC can also be implemented by introducing backward-pumped Raman amplifier that allows a lower input signal power of 2 dB compared with direct transmission. Dual-order Raman based mid-link OPC was tested in a 256 Gb/s dual-polarization 16-QAM transmission over $2\times$ 50.4 km single-mode fiber (SMF) [17], in which the performance evaluation in Q-factor achieved 7 dB reduction in nonlinear threshold and 5 dB optimum launch power, respectively. H. Hu presented an experimental test of $8\times$ 32 Gbaud PDM 16-QAM sub-channels over a 912 km WDM link with OPC based on 500 m HNLF, [18], in which 3 dB nonlinear threshold gain was achieved comparing to the case of no OPC. However, the effect of HNLF length was not discussed [18]. L.B. Du reported an experimental test of a 604.7 Gb/s 16-QAM OFDM rather than CO-OFDM over 800 km fiber with mid-link [19], in which 4.8 dB Q-factor improvement was achieved comparing to the case of no OPC. In [20], 4-QAM CO-OFDM with multiple OPC sections was studied using an analytical model, in which the BER improvements were investigated for dispersion unmanaged (DU) and dispersion managed (DM) system, respectively.

This paper presents a case study of multiple 16-QAM super sub-channels over 800 km CO-OFDM link with mid-link OPC using HNLF. When 16-QAM CO-OFDM signal, including carrier frequency and bandwidth, is given, the investigation focuses on OPC parametric optimization, including the optimization of HNLF length and signal/pump power that inputs into OPC, where four different HNLFs, as illustrative examples, are considered. Furthermore, the investigation focuses on the effects of fiber dispersion, fiber nonlinearity, and ASE noise on the transmission of 16-QAM CO-OFDM signal and the compensation efficiency of using mid-link OPC with different HNLFs. The performance evaluation focuses on the transmission quality of 16-QAM CO-OFDM with mid-link OPC, including conversion efficiency, the received signal constellation, Q-factor gain, and BER at the receiver end. This is important because 16-QAM CO-OFDM signal status is heterogeneous and the mitigation of transmission impairments to the signal is still unclear. On the other

hand, the case study of 16-QAM CO-OFDM with mid-link OPC presented in this paper is different comparing to [17–19], which focus on OPC with OPSK [17], WDM link [18], and OFDM link [19], respectively. Although the performance evaluation in [20] focused on BER versus the signal launch power but without considering of HNLF length and transmission distance.

2. Experiment Setup

Figure 1 shows a diagram of experimental 640 Gbps 16-QAM CO-OFDM transmission over 800 km fiber with a mid-link OPC. Likewise, the same optical simulation system as the laboratory experimental system described in Figure 1 is implemented on the “OPTISYSTEM 15.0” optical simulation platform [21].

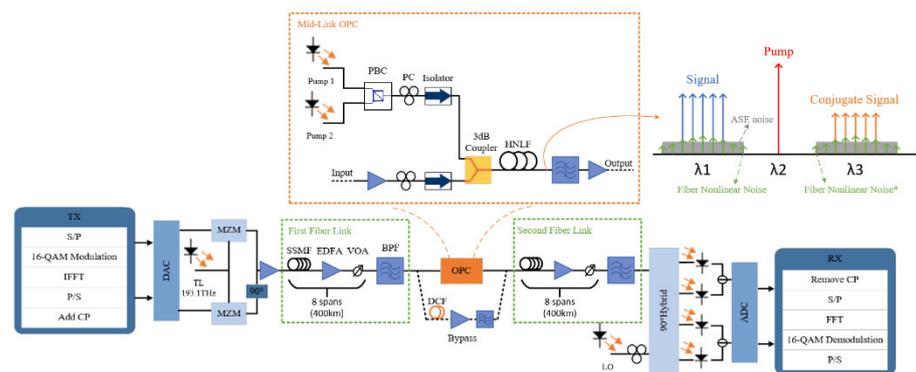


Figure 1. A diagram of 16-QAM coherent-optical orthogonal frequency-division multiplexing (CO-OFDM) transmission with mid-link optical phase conjugation (OPC) compensation.

In the transmitter, two signal streams are loaded into two parallel arbitrary waveform generators (AWG, M8195A: Keysight, Penang, Malaysia) running at 64 GS/s and modulated with a pair of parallel dual-drive Mach–Zehnder modulators (MZM) with opposite polarity, respectively. The signal laser has 193.1 THz (1552.52 nm) central frequency and 0.3 MHz linewidths. At the output of MZM, there are in-phase optical 16-QAM and quadrature-phase optical 16-QAM, respectively, in which each signal stream is composed of 80 sub-carriers. Two optical 16-QAM signal streams, orthogonal to each other, are coupled into a 16-QAM CO-OFDM stream at a bit rate of 640 Gbps. The detailed parameters of the experiment are shown in Table 1.

Table 1. The experiment parameters.

Parameters	Value
Bit rate	640 Gbps
Maximum possible sub-carriers	128
Number of sub-carriers	80
Number of prefix points	10
Number of training symbols	10
Number of pilot symbols	6

The fiber link is implemented by 16 spans of 50 km standard single-mode fiber SMF-28e+ (SSMF, Corning) and an erbium-doped fiber amplifier (EDFA, AEDFA-18-B-FA: Amonics, Hong Kong, China) of 10 dB gain per span. Variable optical attenuators (VOAs, VOAA-15-40-S/FA: OptoQuest, Saitama Prefecture, Japan) are employed at the input of each fiber span to ensure the optical signal power symmetry throughout the system [16]. Band-pass filter (BPF, WSS-1000s: Finisar, Sydney, Australia) with bandwidth 0.32 nm is used to minimize the amplified spontaneous emission (ASE) noise. Alternatively, a dispersion compensated fiber (DCF) with group velocity dispersion (GVD) of -98 ps/nm/km and attenuation of 0.16 dB/km is implemented as a bypass route to evaluate the effect of

fiber nonlinearity on 16-QAM CO-OFDM signal without OPC, where an EDFA to provide 20 dB gain in signal power and an optical BPF of 0.32 nm to minimize the ASE noise are included for comparing with the case of using OPC under the same conditions.

The mid-link OPC has two inputs, including dual pump laser signals at 193.14 THz (1552.20 nm) and the 16-QAM CO-OFDM signal at 193.1 THz (1552.52 nm). A polarization beam combiner (PBC) provides orthogonal polarization for the pumps to achieve polarization-insensitive operation. To prevent useless idles generated by two different pump frequencies, two pumps with the same frequency of 193.14 THz are utilized to improve the phase conjugation efficiency and polarization insensitivity [4]. The optical phase conjugation occurs at a center frequency 193.18 THz (1551.88 nm) based on FWM which benefits from HNLF [13]:

$$\lambda_{con} = 2\lambda_{pump} - \lambda_{sig} \quad (1)$$

At the receiver end, the 16-QAM CO-OFDM signal into 90° hybrid coherent detection which consisting of a Klyia optical hybrid and balanced photodiodes to down-convert the optical signal. A real-time sampling oscilloscope (DSO-X 92804A Infiniium: Agilent, Penang, Malaysia) running at 80 GS/s was used as the analog to digital converter (ADC).

Clearly, when 16-QAM CO-OFDM signal is given, the design of OPC involves the selection of HNLF length and the optimization of signal power and pump signal power that inputs into OPC, which are highly related to the characteristics of HNLF. Hence four different types of HNLFs, as illustrative examples, are considered to study how to select suitable OPC parameters based on the HNLF characteristics. As shown in Table 2, four types of HNLFs, denoted by IDs A to D, are considered, where A represents dispersion-flattened HNLF (DF-HNLF), B is a standard HNLF, C is HNLF with stable phase-matching for improved nonlinear efficiency (HNLF-SPINE), and D is specified HNLF-SPINE with a lower value of fourth-order fiber dispersion coefficients. Note that the dispersion parameters are measured by an Agilent 86037C dispersion test set [22].

Table 2. Four types of highly nonlinear fiber (HNLF) are considered for OPC.

HNLF	A	B	C	D
λ_0 [nm]	1541.3	1546.7	1542.9	1545.4
S_0 [ps/nm ² km]	0.0074	0.017	0.072	0.07
α [dB/km]	0.76	0.74	0.83	0.47
n_2 [m ² /W]	30.467	31.989	27.392	18.951
γ [W ⁻¹ /km ⁻¹]	10.8	11.3	9.7	6.7

3. Optical Phase Conjunction (OPC) Parametric Optimization

Figures 2 and 3 illustrate the measured conversion efficiency and BERs at the receiver end versus the signal power and the pump signal power input into OPC, respectively. The conversion efficiency is defined as the power ratio of the resulting phase conjugate signal to the transmitted signal. It is well-known that the control of signal power and pump signal power at the input of OPC is an important approach to eliminate the nonlinear distortion such as SPM and pump stimulated Brillouin scattering (SBS) [23]. Figure 2 shows that the balance of BER and conversion efficiency at the receiver end requires the input signal power of OPC to be −2.5, −3.3, −2.4, and 1.7 dBm for HNLF A–D, respectively. Likewise, Figure 3 shows that the balance of BER and conversion efficiency at the receiver end requires the pump signal power to be 23, 23, 23, and 21 dBm for HNLF A–D, respectively.

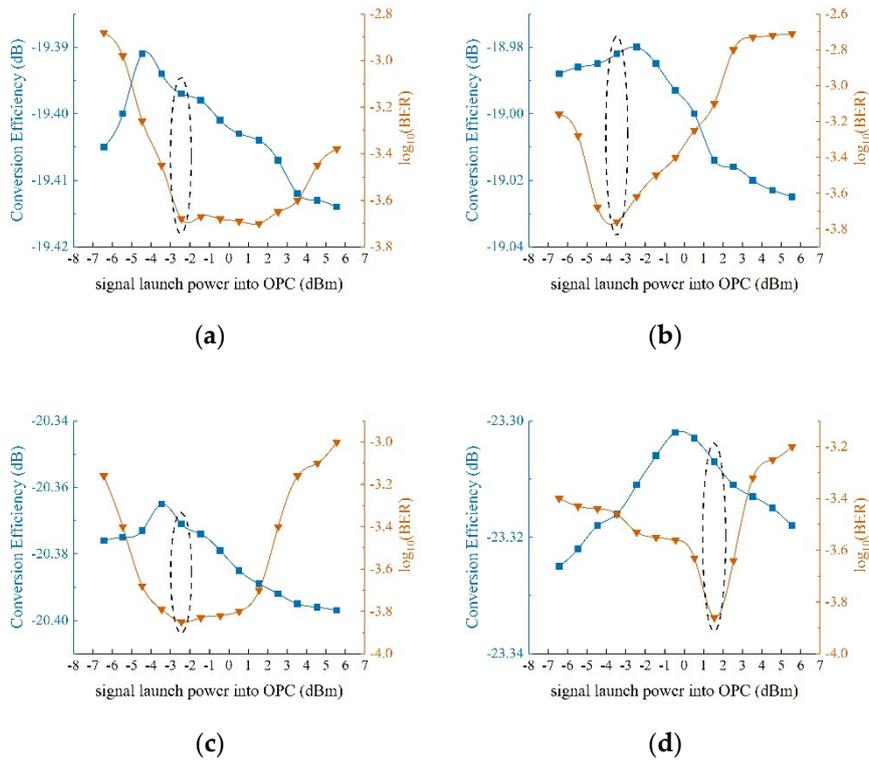


Figure 2. Measured conversion efficiency in square symbol line and bit error rates (BERs) in triangle symbol line versus the signal power input into OPC. (a) HNLF A; (b) HNLF B; (c) HNLF C; (d) HNLF D.

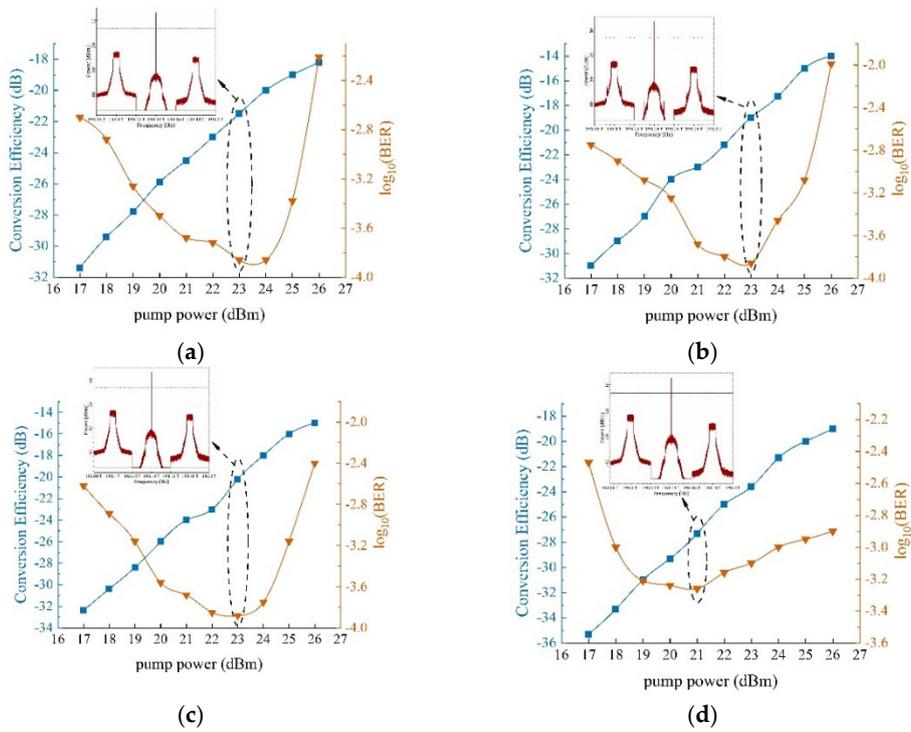


Figure 3. Measured conversion efficiency in square symbol line and BERs in triangle symbol line versus the pump signal power input into OPC. (a) HNLF A; (b) HNLF B; (c) HNLF C; (d) HNLF D.

4. Performance Evaluation

Figure 4 illustrates a comparison of Q-factor versus HNLF length for HNLF A–D, which are obtained by simulations using “OPTISYSTEM 15.0” [21]. On other hand, Q-factor can be calculated from the measured BER using Equation (2), which is provided by [11].

$$Q(\text{dB}) = 20\lg[\sqrt{2} \times \text{erfcinv}(2 \times \text{BER})] \quad (2)$$

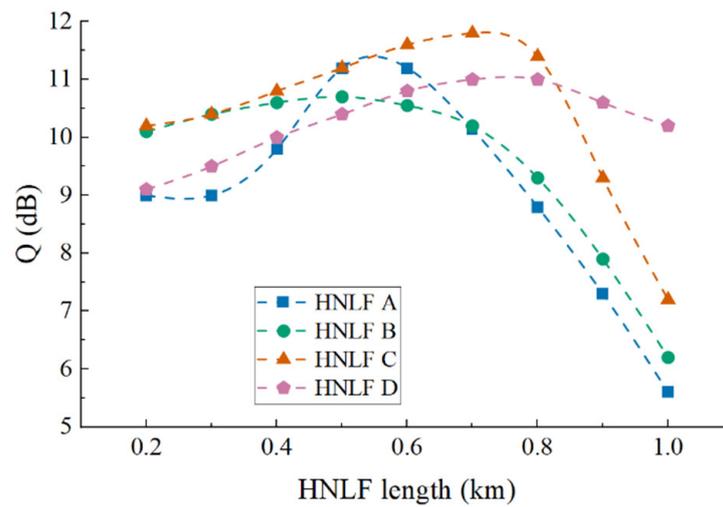


Figure 4. A comparison of Q-factor versus HNLFs length.

Note that the numerical results illustrated in Figure 4 are obtained under the conditions that the input signal power and the pump signal power of OPC are set to the optimum values obtained by Figures 2 and 3 for HNLF A–D, respectively. Figure 4 shows that the HNLF length corresponding to the optimum Q-factor value for HNLF A–D is 550, 500, 750, and 800 m, respectively. Equation (3) shows that the deterioration power of OPC is sensitive to HNLF length [2].

$$P_{\text{deterioration}} = 3N_{SC}^2(\gamma L)^4 P_{\text{pump}}^2 P_{SC}^3 \quad (3)$$

where, N_{SC} is the number of sub-carriers, $\gamma = \frac{2\pi n_2}{\lambda_0 A_{eff}}$ is the non-linearity factor in the HNLF, L is the length of HNLF, P_{pump} is the pump signal power, P_{SC} is the power of a single sub-carrier.

Figure 5 illustrates the received 16-QAM signal constellation diagrams at the receiver end for different scenarios, where received OSNR is set up to 34 dB. The aim is to evaluate the OPC compensation capability. It is known that fiber nonlinear effect, dispersion effect, and ASE noise accumulated within the transmission bandwidth are the major interference in optical transmission systems, especially in long haul transmission. After an optical BPF of 0.32 nm is adapted for reducing the out-band ASE noise effect, it can be seen that constellation rotation obviously due to fiber nonlinearity in Figure 5a. The constellation diagram of OPC with different HNLF scenarios as shown in Figure 5b–e demonstrates that OPC can effectively compensate the fiber dispersion and nonlinearity. In contrast, as shown in Figure 5a, although DCF is used for dispersion compensation, the constellation points are still scattered compared to that of using OPC. It clearly demonstrates that dispersion compensation using OPC is better than that of using DCF [9].

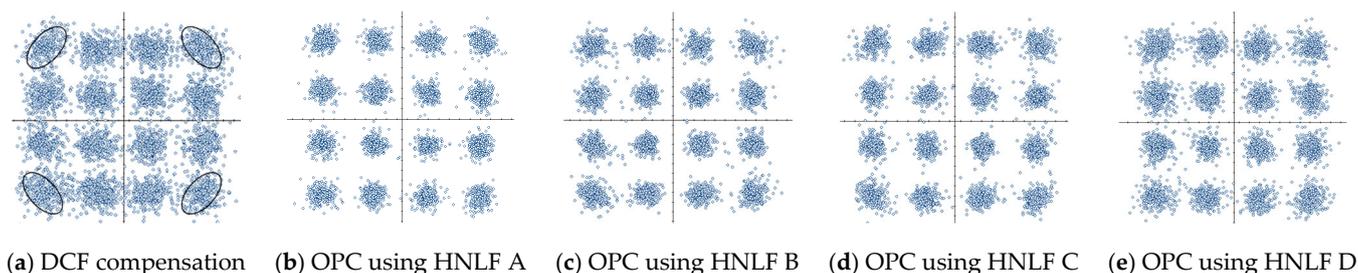


Figure 5. Received 16-QAM signal constellation diagram after 800 km transmission: (a) Dispersion compensation using dispersion compensated fiber (DCF); (b) mid-link OPC using 550 m HNLF A; (c) mid-link OPC using 500 m HNLF B; (d) mid-link OPC using 750 m HNLF C; (e) mid-link OPC using 800 m HNLF D.

Figure 6 shows Q-factor versus OSNR for different HNLF scenarios. Table 3 presents the numerical results of conversion efficiency, Q-factor gain, and BER, where received OSNR is 34 dB. It can be observed that the mid-link OPC with 550 m HNLF A has Q-factor of 9.8 dB, BER of 6.1×10^{-4} and conversion efficiency of -22 dB. In contrast, the mid-link OPC with 800 m HNLF D has Q-factor gain of 8.9 dB, BER of 2.7×10^{-3} , and conversion efficiency of -22.6 dB. This can be explained by Equation (4), that the power spectrum of OPC, denoted as P_{OPC} , is in direct proportion to the term $(\gamma L)^2$ [2].

$$P_{OPC} = (\gamma L)^2 P_{pump}^2 P_{SC} \tag{4}$$

The mid-link OPC improves Q-factor of 3 dB in average and enhances the BER performance nearly two orders magnitude comparing to the case of no OPC.

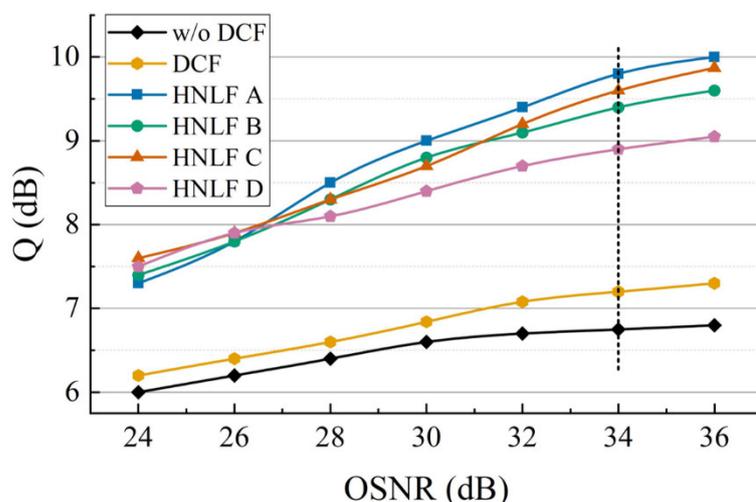


Figure 6. A comparison of Q-factor gains versus optical signal-to-noise ratio (OSNR) after 800 km transmission.

Table 3. A comparison of OPC performance at OSNR 34 dB.

Parameters	BER	Q [dB]	CE [dB]
Without compensation	1.5×10^{-2}	6.8	-
With dispersion compensation fiber	1×10^{-2}	7.2	-
with mid-link OPC using 550 m HNLF A	6.1×10^{-4}	9.8	-22
with mid-link OPC using 500 m HNLF B	1.6×10^{-3}	9.4	-22.4
with mid-link OPC using 750 m HNLF C	1.3×10^{-3}	9.5	-20.6
with mid-link OPC using 800 m HNLF D	2.7×10^{-3}	8.9	-22.6

5. Conclusions

This paper presents quantitative measurement through an experimental test of 640 Gbps 16-QAM CO-OFDM over 16×50 km optical fiber link with a mid-link OPC, which is implemented using FWM via HNLF. For a given 16-QAM CO-OFDM signal, the design of OPC needs to focus on the selection of HNLF length and determine signal power and pump signal power at the input of OPC, which are highly related to the characteristics of HNLF. There are four different types of HNLFs investigated. The numerical results show that for a given 16-QAM CO-OFDM signal at 193.1 THz (1552.52 nm), the optimum length for HNLF A–D is 550, 500, 750, and 800 m, while the optimum signal power into OPC is -2.5 , -3.3 , -2.4 , and 1.7 dBm and the optimum pump power is 23, 23, 23, and 21 dBm, respectively. The performance evaluation is presented in terms of OPC conversion efficiency, Q-factor improvement, received signal constellation, and BER at the receiver end. It is important because 16-QAM CO-OFDM signal status is heterogeneous and the mitigation of transmission impairment to the signal is still unclear. The study of received 16-QAM signal constellation diagrams shows that OPC plays a better role for compensating fiber dispersion and nonlinearity effect comparing to the case of using DCF. The numerical results show that mid-link OPC using 550 m HNLF A provides Q-factor of 9.8 dB and BER of 6.1×10^{-4} , which has the Q-factor improvement of 3 dB and nearly two orders magnitude improvement in BER comparing to the case of no OPC. The evaluation methodology presented in this paper provides useful information for OPC design.

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