Linear and Kerr nonlinear compensators by continuous-variable photonic quantum computing for digital coherent transmission systems

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***Abstract*—We propose linear and Kerr nonlinear compensators by continuous-variable photonic quantum computing for digital coherent transmission systems. The numerical simulation shows the possibility of compensators for chromatic dispersion and Kerr nonlinearity occurred in fibers.**

Keywords—digital coherent transmission, nonlinear compensation, photonic computing, quantum computing

I. INTRODUCTION

Internet data traffic has been growing rapidly in recent years. This requires an increase in the transmission capacity of long-haul optical networks. To increase the transmission capacity, the spectral efficiency (SE) should be improved because available optical bandwidth of optical amplifiers is limited. According to the Shannon's theorem, the upper limit of SE is determined by the logarithm of the signal-to-noise ratio (SNR). However, when the optical launch power into a fiber significantly increased to improve the SNR, nonlinear interference noise (NLIN) due to Kerr nonlinearity appears, which in turn degrades the SNR [1]. To overcome this problem, digital nonlinear compensators (NLCs) for NLIN by digital signal processing (DSP) have been studied [2-5]. The digital back propagation (DBP) [2-4] is the best-known method, in which nonlinear Schrödinger equation (NLSE) is numerically solved backwards to remove chromatic dispersion and nonlinear phase rotation occurred in the fibers. Although the DBP is known as the best compensator in terms of the compensation performance among NCL methods, the huge computational complexity is not suitable for hardware implementation. Perturbation theory based NLC offers moderate NLC performance but reduced computational complexity [3]. However, as these NLC methods rely on DSP, electrical power consumption and calculation delay are significant issues.

To offload huge computation in DSP, analog computing such as photonic processors [6-9] has been garnering attention. In the photonic processors, input data is encoded in a power and/or phase of a light and fed to optical devices such as interferometers for data processing. The advantages of the photonic processors are lower electrical power consumption, smaller calculation delay, and higher throughput [8]. However, analogue computing cannot correct for errors induced by noise in the calculation process. The errors become a significant issue in large-scale photonic processors [9]. This means that the scaling up computational depth and width is challenging.

In this work, we propose linear and Kerr nonlinear compensators by quantum computing (QC) [10-18], which is expected to have error correctability. We exploit the power of QC that can simulate dynamics arising from quantum mechanics significantly faster than classical counterpart [19]. Since the dispersion and Kerr effects can be described quantum mechanically [20], QC is able to efficiently simulate optical systems under these effects. To construct an effective compensator using QC, we utilize the framework called variational quantum algorithms [21], where one iteratively optimize the operations in a quantum circuit to obtain a circuit suited for a specific task. We propose to use a quantum circuit consisting of alternating layers of linear interferometer and Kerr gates, and optimize it within the framework. This form of the circuit is naturally realizable with photonic QC. The numerical simulation shows the possibility of compensators for chromatic dispersion and Kerr nonlinear phase rotation occurred in fibers using a 32 GBd. 16 QAM signal.

II. LINEAR AND KERR NONLINEAR COMPENSATORS BY CONTINUOUS-VARIABLE PHOTONIC QUANTUM COMPUTING

Figure 1 shows the proposed photonic QC based linear and nonlinear compensator. We assumed that a QAM signal was transmitted over a fiber has chromatic dispersion and Kerr nonlinearity and received by a coherent receiver. After an analogue to digital conversion, the sample, $y \in \mathbb{C}$, was sent to a photonic QC. Here, we assume that the photonic QC has n *qumodes*, which corresponds to different paths on the photonic QC chip [22]. In the photonic QC, a complex value can be encoded to a continuous-variable of a qumodes, namely, an electrical field, by a displacement gate. A time series of y with the length of n, $\boldsymbol{y} = [y_{t=0}, y_{t=1}, y_{t=2}, \dots, y_{t=n-1}]$ was

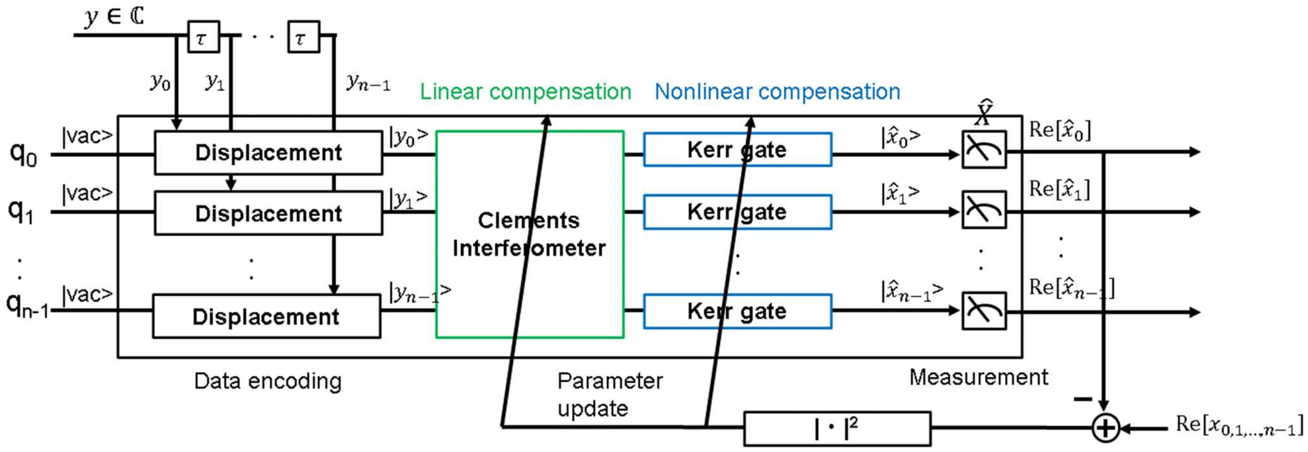

Figure 1 The concept of linear and nonlinear compensators using n-qumodes photonic QC.

encoded to electrical fields of n qumodes by n displacement gates. The qumodes were processed by a universal unitary operator based on the programable Clements interferometer [23]. This enables compensation for a linear inter-symbol interference (ISI) occurred within the n symbols. Then the qumodes were sent to programable Kerr nonlinear gates, where the degree of nonlinearity is programable. Finally, the electrical fields of qumods were detected by homodyne detections. Due to the Heisenberg's uncertainty principle, we can only extract one of in-phase or quadrature-phase component of the electrical field simultaneously. Therefore, we ran the quantum QC and measure the qumodes twice to get both of the in-phase and quadrature-phase components. After the homodyne detection, a mean squared error (MSE) was calculated by the difference between the measured in-phase (or quadrature-phase) components and ideal signals. The parameters of the Clements interferometer and Kerr gates were updated iteratively to minimize the error using a conventional gradient descent algorithm and back-propagation method [24,25].

III. SIMULATION SETUP

Figure 2 show the simulation setup. We assumed a 32 GBd. 16QAM signal was transmitted. The signal was transmitted over 3 spans consist of 60-km fibers and EDFAs. The attenuation coefficient of the fibers was 0.2 [dB/km]. The NF of EDFAs was 5 dB. The launched power was set to 6 dBm. To confirm the compensation performance of the proposed QC, we swept the chromatic dispersion and nonlinear coefficients from 0 to 20 [ps/nm/km] and 0 to 1.5 [1/W/km], respectively. After the transmission, the signal was processed by the photonic QC to compensate for chromatic dispersion and Kerr nonlinearity.

The photonic QC was simulated by the strawberry field and pennylane software, these are open source software implemented by Python [26]. Unlike an actual photonic QC, the computing time of classical simulation of the photonic QC growth rapidly as the number of qumodes increases. Therefore, the number of qumodes was five due to the limitation of computing time. To limit an ISI due to the chromatic dispersion within 5 symbols, we set the frame length of a 16 QAM signal to 5 symbols. The choice of simulation algorithm also contributes to the computing time of the simulation. A gaussian simulator (*strawberryfields.gaussian* [27,28]) can simulate gates efficiently exclude Kerr nonlinear gates. On the contrary, a fock simulator (*strawberryfields.fock* [27,28]) can simulate Kerr nonlinearity gates but it requires huge computational time. In our simulations, we individually simulated and optimized linear and nonlinear compensators using gaussian and fock simulator, respectively. The number of epochs and learning rate of Adam gradient descent optimizer were 64 and 10^{-1}, respectively.

IV. RESULTS

Figure 3 shows simulation results of the photonic QC based linear compensator. The nonlinear coefficient was fixed to 1.3 [1/W/km]. Figure 3(a) shows the MSE with or without the linear compensator as a function of a chromatic dispersion coefficient. The MSE was significantly improved by the proposed linear compensator. Figure 3(b) shows the constellation maps with or without the linear compensator at a chromatic dispersion coefficient of 20 [ps/nm/km]. The

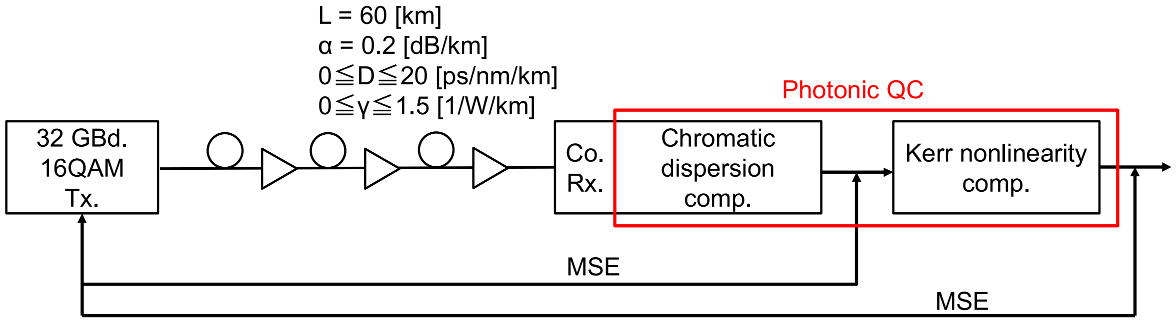

Figure 2 Simulation setup.

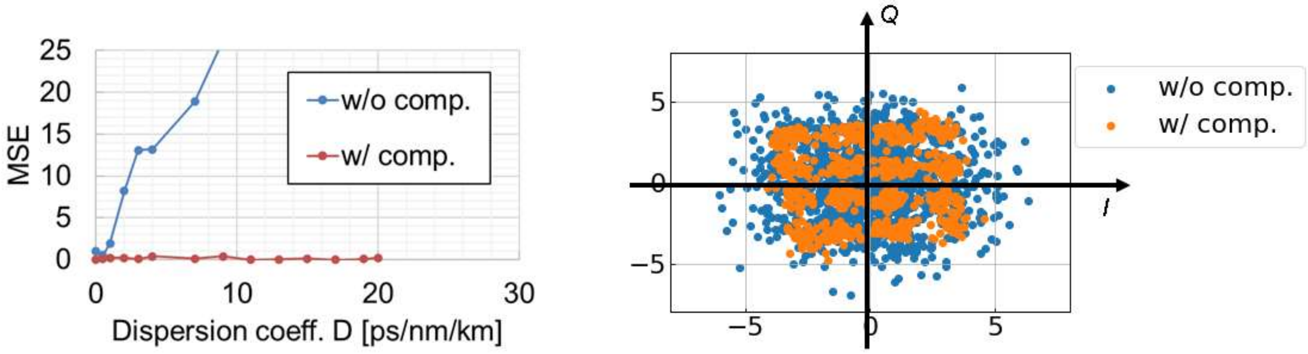

Figure 3 Chromatic dispersion compensation by the photonic QC based linear compensator.

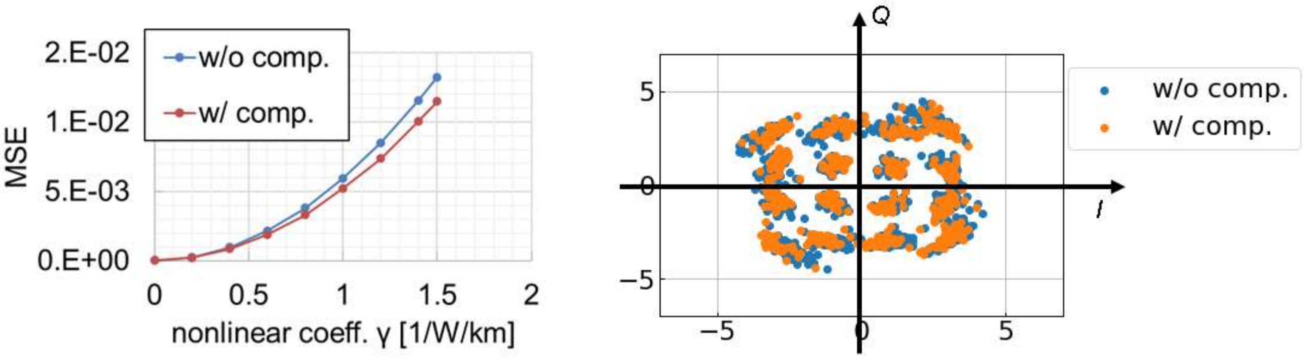

Figure 4 Kerr nonlinearity compensation by the photonic QC based nonlinear compensator.

constellation map of the 16 QAM signal was clearly recovered by adaption of the proposed linear compensator. The residual distortion would be further reduced by reducing the learning rate in the Adam gradient descent optimizer and increasing the number of epochs, although this would increase the computation time.

Figure 4 shows simulation results of the photonic QC based Kerr nonlinear compensator. A chromatic dispersion coefficient was fixed to 20 [ps/nm/km] and ideal chromatic dispersion compensation was assumed. Figure 4(a) shows the MSE with or without the Kerr nonlinear compensator as a function of a nonlinear coefficient. The MSE was improved by the proposed nonlinear compensator. Figure 4(b) shows the constellation maps with or without the nonlinear compensator at a nonlinear coefficient of 1.3 [1/W/km]. The nonlinear phase rotation due to the Kerr nonlinearity occurred in fibers was mitigated by proposed nonlinear compensator. Thus, the possibility of linear and Kerr nonlinear compensator based on a photonic QC was confirmed.

V. DISCUSSION

To further mitigate NLIN, a multi-layer architecture with alternating layers of linear and nonlinear compensator inspired by DBP algorithm should be effective because it can compensate for an interaction between chromatic dispersion and Kerr nonlinear phase rotation. However, it increases the depth of the quantum circuit and computation time for classical simulation.

In order to implement the proposed compensator on real photonic QCs, a realization of nonlinear Kerr gates is a significant issue because it is difficult to excite Kerr nonlinearity using a weak light for quantum computing. Measurement-based quantum computations would be a promising method to realize non-Gaussian elements such as Kerr nonlinearity indirectly [11]. We can also use universal quantum computers to emulate perfect photonic QCs to realize Kerr gates. Another issue is the required number of qumodes. In our proposed compensator, the required number of qumodes is proportional to an accumulated chromatic dispersion. Therefore, it is challenging to introduce the compensator for long-haul transmission systems, although NLIN becomes significant issue in the long-haul transmission systems [1].

VI. CONCLUSION

We proposed linear and Kerr nonlinear compensators based on a continuous-variable photonic quantum computing. Using a 32 GBd. 16 QAM signal transmitted over 3 × 60-km fibers, the possibility of the compensators were confirmed by numerical simulations on classical computers. The issues toward performance improvements and physical implementation of the proposed compensators were discussed.

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