

Article

Beyond 100G: All-Optical Processor for High-Capacity Access~Networks

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Abstract: We propose a novel approach to mitigate the limitations of high-speed Passive Optical Networks (PONs) by introducing an all-optical processor. This solution addresses the escalating demand for higher data rates and improved performance in future access networks. The all-optical processor leverages optical signal processing to enhance system efficiency and reduce power consumption compared to traditional electrical methods. Specifically, we explore the processor's dual functionality in performing all-optical equalization and chromatic dispersion compensation. Our research includes a comprehensive analysis of the processor's design, operational principles, and system validation through extensive simulation studies, demonstrating significant improvements in signal quality and overall network performance. The results indicate that the all-optical processor not only relaxes the DSP and power requirements but also outperforms the more sophisticated digital counterpart methods.

Keywords: passive optical networks (PON); optical signal processing; chromatic dispersion compensation; optical equalization; digital signal processing (DSP); machine learning optimization

1. Introduction

The post-pandemic era has placed enormous strain on modern networks that strive to adapt to a rapidly changing landscape. The relentless traffic growth, driven by the explosion of bandwidth-intensive applications, such as high-definition video streaming, cloud computing, and increasingly sophisticated AI services, alongside the proliferation of connected devices has pushed the telecommunication networks to their ultimate operational limits. Amidst this unprecedented digital transformation, access networks, the vital link connecting end-users to the core of the telecommunication network, are currently strained under the weight of escalating data traffic and the need for universal, seamless connectivity. The adoption of the 50G PON standard signifies progress in meeting these demands through the use of high-speed IM/DD transceiver solutions, yet the industry and academia are collectively navigating the discussion towards 100G or even beyond.

Two paths emerge. The first involves the adoption of a new generation of IM/DD transceivers capable of supporting 50 Gb/s Non-Return-to-Zero (NRZ) signals and extending to 100 Gb/s by means of four-level Pulse Amplitude Modulation (PAM4). The implementation of IM/DD systems offers simplicity and cost and power efficiency and has been traditionally considered as the ideal solution for the "last mile" of network connectivity (10G and 25G PON standards). Nevertheless, as the speed requirements of the access networks increase beyond 100G, the cost-performance benefit of IM/DD systems becomes questionable due to the severe effect of chromatic dispersion, which limits the PON reach.

Various approaches have been proposed to compensate for the induced impairments utilizing sophisticated electrical equalization techniques [1–4] and neural-network-based approaches [5–10]. Additionally, solutions involving different types of amplification [11,12], alternative modulation schemes [13], or hybrid approaches [14–16] have been demonstrated.



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However, all these approaches increase the overall system complexity as well as the power consumption.

The second path is the employment of coherent solutions, which are increasingly penetrating applications traditionally dominated by IM/DD technology [17]. The integration of coherent optics into a PON offers specific advantages, and extensive research has been conducted in this direction [18–21]. However, the adoption of coherent technologies in the next generation of PONs is not without significant challenges, the most important among these being the implementation cost. Given that PON equipment involves the end-users, any increase in implementation cost is amplified exponentially. The incorporation of an additional laser for the LO, the increase in the number of photodetectors used, the more sophisticated modulator designs, power-hungry DSP algorithms, and increased electronics complexity not only escalate costs but also augment the power consumption and the overall system complexity. Furthermore, upstream burst mode detection becomes notably more intricate with coherent optics compared to IM/DD approaches. These challenges underscore the necessity for careful consideration and strategic planning in navigating the transition towards the next generations of PON technologies.

The complexity and power consumption of electrical and machine learning approaches, particularly as PON technologies evolve towards higher speeds, have highlighted the potential advantages of optical processing equalization techniques. The exploration of optical methods, long considered for their efficiency and performance benefits, has been intensified to mitigate the limitations of traditional electrical solutions, such as reliance on power-hungry DSP algorithms and complex electronic circuits, while maintaining similar, if not better, performance. Various approaches have been explored, making optical signal processing a promising candidate for the next generations of PONs [22–27].

In this manuscript, we propose a novel approach to mitigate the limitations of migrating towards higher-speed PONs while exploiting the benefits of IM/DD solutions by introducing an all-optical processor (AOP). The AOP leverages the benefits of optical signal processing to enhance system efficiency and reduce power consumption compared to traditional digital methods. Specifically, we explore the dual functionality of the processor in performing all-optical equalization and chromatic dispersion compensation. This study presents a comprehensive analysis of the processor's design, operational principles, and system validation, demonstrating significant improvements in signal quality and overall network performance.

The rest of the paper is organized as follows: In Section 2, we present an overview of the standards for 50G and the evolution towards 100G PON. Section 3 describes the operating principle and circuit design of the proposed AOP. In Sections 4 and 5, we detail the experimental setup and results. Finally, Section 6 concludes the work.

2. Passive Optical Network Standardization Overview

This section focuses on the 50G PON and the emerging 100G PON standards that serve as a reference for our study.

2.1. 50G Passive Optical Network

The 50G PON standard, as officially standardized by the International Telecommunication Union (ITU-T G.9804.3), continues the point-to-multipoint (PtMP) architecture used in GPON and XGS-PON, rendering it suitable for diverse deployment scenarios, including fiber-to-the-home (FTTH) scenarios. Supporting symmetrical data rates of 50 Gbps for both downstream and upstream transmissions, 50G PON utilizes a downstream wavelength range of 1340–1344 nm, as agreed upon by both the IEEE [28] and ITU-T [29]. This specific wavelength range ensures compatibility with existing optical distribution networks (ODNs), allows for coexistence with legacy PONs, and minimizes dispersion to limit inter-symbol interference over the ODNs.

One of the major challenges in PONs is achieving high link budgets without the use of optical amplification. This necessitates transmitters with an extremely high modulated

output power and high dynamic extinction ratio (ER). In certain scenarios, a link budget of up to 30 dB may be required. To meet these demanding power budgets, 50G PON systems rely on avalanche photodiode (APD)-based receivers due to their higher sensitivity compared to the more common and less expensive PIN receivers.

Moreover, the use of APDs, especially low-rate and bandwidth-limited devices such as 25G APDs, significantly reduces the overall cost of the optical network units (ONUs). This cost reduction is crucial because, in real deployments, the number of ONUs is much larger than the number of optical line terminals (OLTs), making the combined ONU cost a major factor. The use of DSP enables mature 25G APDs to handle 50G signal transmissions, thereby enhancing overall cost effectiveness even more [30].

2.2. The Road to 100G PON

In the transition from 50G PON to 100G PON, both coherent and IM/DD solutions have been explored to meet the increasing demands for higher data rates. Building on the foundation of 50G PON, our approach follows the parameters and modifications proposed by [31] to leverage the cost efficiency and simplicity of IM/DD systems for 100G PON [32].

The development of 100G PON involves critical modifications to components such as transmitters and receivers, which need to operate at higher bandwidths to support the increased data rates. This adjustment is necessary to maintain signal integrity over the optical distribution network (ODN). Improved digital signal processing (DSP) is crucial for managing the increased impact of fiber dispersion and other signal distortions at higher data rates. Stronger DSP equalization and enhanced Forward Error Correction (FEC) mechanisms are required to support higher error rates, ensuring reliable data transmission under challenging conditions. Maintaining a power budget similar to 50G PON is essential for 100G PON feasibility. The launch power for 100G transmitters remains within the same range as 50G PON, allowing the existing infrastructure to be used without significant modifications.

By addressing these technical challenges, 100G PON aims to provide high-performance, cost-effective solutions for next-generation PONs. The proposed parameters and changes ensure that 100G PON can meet the increasing demands for higher data rates while maintaining compatibility with existing network infrastructures.

3. Overview of the Proposed All-Optical Processor

The implementation of PAM4 in 50G and 100G PON significantly increases the demands on DSP due to the higher sensitivity penalties and linearity requirements of PAM4 compared to traditional NRZ modulation. These impairments are handled by stronger DSP equalization techniques, such as feed-forward/decision feedback equalizers (FFE/DFE), or by using machine-learning-based equalization methods, such as deep neural networks (DNN) [33,34].

To mitigate the increased computational demands of DSP, we propose integrating an AOP, which can effectively handle the computational needs, reducing latency and power consumption while improving processing performance. The proposed AOP aims to exploit the established low-cost technology of IM-DD PON systems to extend their operation speed at 100 and 200 Gb/s employing current-generation optoelectronic components, increasing their component bandwidth limitations by at least 40%. Moreover, the AOP is considered part of the transmitter at the optical line terminal (OLT), keeping the overall ONU cost and complexity low and comparable to 50G PON systems and rendering the benefits of IMDD technologies up to 200 Gb/s. Figure 1 shows a functional block diagram of the AOP, which stands out due to its unique architecture and dual functionality, enabling it to selectively perform two critical tasks, all-optical equalization and chromatic dispersion compensation, depending on the dominating system impairment, at the dictated operating speed. In the present study, fiber lengths of a maximum of 15 km are considered, rendering linear effects (optical propagation loss, chromatic dispersion, and polarization mode dispersion) the dominating signal impairment mechanism. It is noteworthy that, for future PON

scenarios under consideration which target supporting an extended reach of up to 80 km with variable split ratios [Huawei, CableLabs], nonlinear transmission impairments will play a more crucial role that will likely necessitate the adoption of coherent DSP solutions. To this end, the proposed AOP aims to demonstrate the viability of IMDD systems at even higher speeds assisted by means of a machine learning (ML)-assisted algorithms.

This processor leverages the adaptability of an optical switcher to alternate between tasks. In switch state 0, the AOP functions as an optical equalizer. In switch state 1, the AOP acts as a chromatic dispersion compensation filter. This versatile switching capability enhances the system’s adaptability and efficiency.

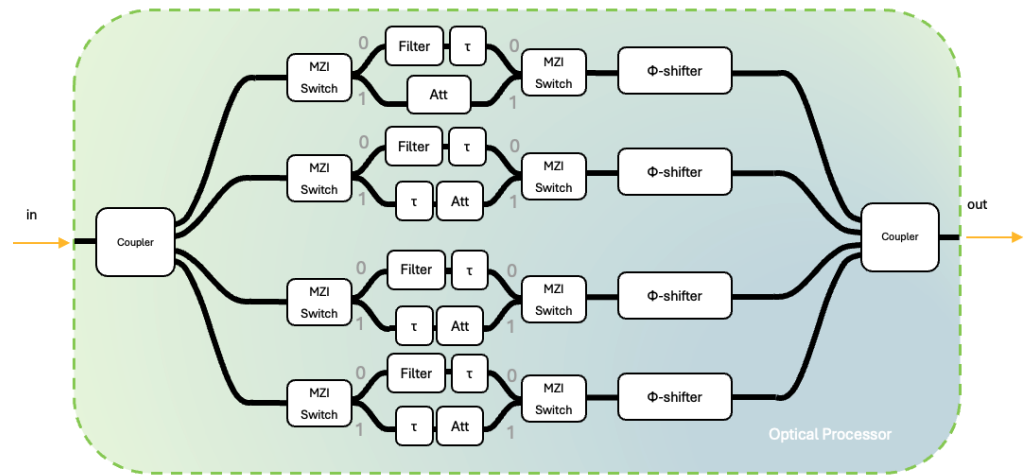


Figure 1. Schematic of the all-optical processor.

3.1. Task 1: All-Optical Processor as an Equalizer

The first task of the AOP involves all-optical equalization, as illustrated in Figure 2. This functionality is designed to mirror the inverse of the channel’s frequency response as closely as possible. The input signal is first divided into four duplicates using cascaded couplers. Each duplicate is then sequentially delayed by a time increment τ , which approximates the duration of a single transmission symbol. The system’s adaptability is enhanced through operational tuning, which allows adjustment of τ . After the delay, each signal is amplified and phase-shifted to ensure either constructive or destructive interference across the branches, thereby controlling the signal’s gain. The overall output is a linear combination of each branch’s input, as described by Equation (1):

$$P_{out}(t) = \frac{1}{n} \sum_{i=1}^n g_i P_{in}(t - i\tau) \tag{1}$$

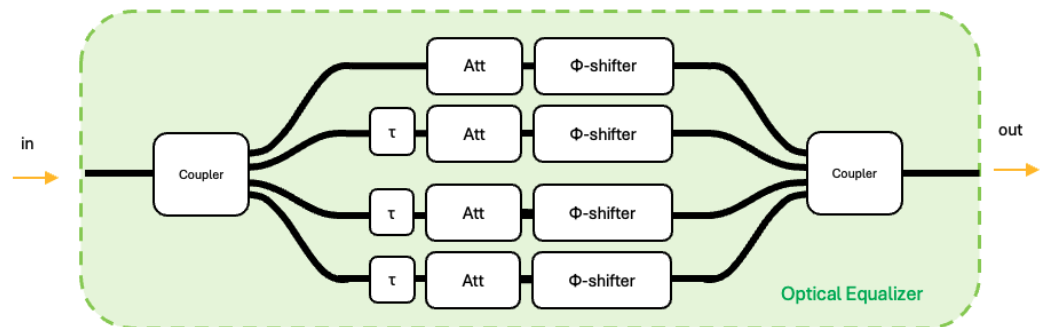


Figure 2. Operation of the AOP at 0 state and optical equalizer.

The operational principle and schematic of this task highlight the processor’s ability to act as an optical equalizer, providing an efficient solution to counteract signal impairments and mitigate bandwidth limitations without relying on conventional DSP techniques. This is particularly advantageous in PONs, which are often bandwidth limited to remain cost effective.

3.2. Task 2: Chromatic Dispersion Compensation Filter

The processor’s second functionality, the chromatic dispersion compensation filter (CDCF), depicted in Figure 3, addresses chromatic-dispersion-induced phenomena, a vital requirement for preserving signal quality over long distances in PONs.

Chromatic dispersion (CD) in optical fibers leads to two significant phenomena: inter-symbol interference (ISI) and power fading. ISI occurs when dispersion causes signal pulses to spread out and overlap with adjacent pulses, making it challenging for the receiver to distinguish between successive bits and thereby degrading the bit error rate. Power fading results from varying delays experienced by different frequency components of the signal, leading to constructive and destructive interference at the receiver, which causes fluctuations in the received signal power. Both ISI and power fading are exacerbated by higher baud rates and longer fiber lengths as increased data rates result in shorter pulses that are more susceptible to spreading, and longer distances accumulate more dispersion effects.

The CDCF performs spectral slicing using cascaded couplers and finely tuned filters to divide the optical signal into four subbands. Each subband undergoes specific time delays and phase shifts, calculated to neutralize CD-induced delays that vary with frequency. The flexible design allows for tailored adjustments to phase and delay settings. This precision maintains the reassembled signal’s structure and content, avoiding the power fading effect and enhancing detection quality.

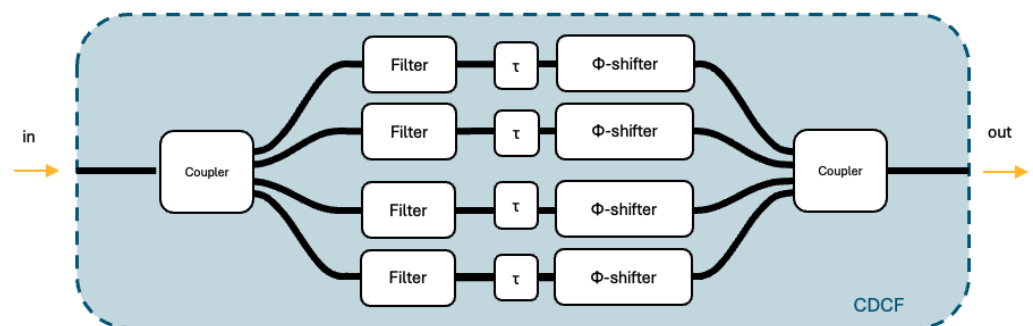


Figure 3. Operation of the AOP at state 1 and CDCF.

4. Simulation Setup

In this section, we detail the simulation setup and performance evaluation for the 100G and 200G PON systems. Our objective is to utilize existing equipment compatible with the 50G standard or proposed 100G specifications and employ higher-order modulation schemes to significantly increase data rates. By using PAM4 instead of the conventional NRZ, we aim to achieve 100 Gbps and 200 Gbps, respectively. This approach leverages equipment intended for 50G or 100G PON to effectively double the transmission capacity, achieving 100G and 200G PON using 50G and 100G equipment, respectively.

Higher-order modulation schemes like PAM4 offer increased spectral efficiency but introduce a sensitivity penalty due to their multiple levels and higher linearity requirements at the transmitter. For instance, transitioning from 25G NRZ to 50G PAM4 using the same receiver incurs a sensitivity penalty of 8–9 dB, typically preventing PAM4 from meeting the 29 dB power budget without digital signal processing (DSP) and/or receiver pre-amplification. These limitations necessitate advanced signal processing techniques, underscoring the necessity of the AOP.

Table 1 outlines the key simulation parameters used for both 100G PON and 200G PON systems. These parameters were selected to accurately model the performance of the PON systems under realistic operating conditions.

Table 1. Parameters for 50, 100, and 200G PON.

Parameters	50G PON Standard [29]	Proposed 100G PON [31]	Simulated 100G PON	Simulated 200G PON
Tx Bandwidth	22 GHz	75 GHz	22 GHz	75 GHz
Tx Launch Power, C+	10 dBm	10 dBm	10 dBm	10 dBm
Wavelength	1340–1344 nm	1318–1322 nm	1344 nm	1344 nm
Rx Bandwidth	30 GHz	50 GHz	30 GHz	50 GHz
Rx ROP	−20.75 dBm	−20.75 dBm	−19 dBm	−17 dBm
Rx Responsivity	0.8 A/W (APD)	0.6 A/W (PIN)	0.8 A/W (APD)	0.8 A/W (APD)
Bit Rate	50 Gbit/s	100 Gbit/s	100 Gbit/s	200 Gbit/s
Modulation Format	NRZ	NRZ	PAM4	PAM4
Reach	20 km	10 km	20 km	10 km
Equalization	13FFE	21FFE + 3DFE	AOP (+ 5FFE)	AOP (+ 5FFE)

In Figure 4, the system configuration illustrates a downstream link for a 100/200G PON operating in the O-band (1344 nm), designed to support 64 users within a radius of up to 20 km. The simulation setup and performance evaluation were conducted using VPItransmissionMaker™ 11.4 software.

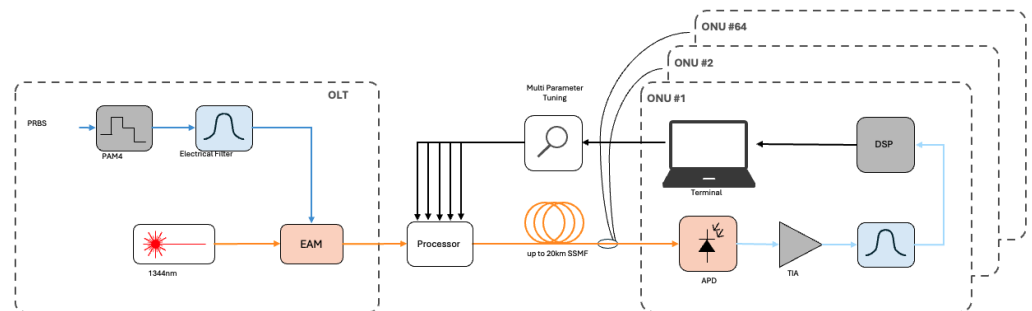


Figure 4. Simulated PON downstream link configuration with ML-assisted optical processor for 64 users.

At the optical line terminal (OLT), the signal is modulated onto an optical carrier using an Electro-Absorption Modulator (EAM). The Tx 3 dB electro-optical bandwidths for the different scenarios are detailed in Table 1, achieved through a fourth-order Bessel electrical filter. This modulated signal is transmitted over a Standard Single-Mode Fiber (SSMF) span of up to 20 km, with a chromatic dispersion parameter of $D = 2.44 \text{ ps}/(\text{km}\cdot\text{nm})$, to the optical network unit (ONU).

At the ONU side, an avalanche photodiode (APD) with 0.8 responsivity, paired with a Transimpedance Amplifier (TIA) and a post-amplifier, effectively detects and amplifies the incoming optical signal. The receiver (Rx) 3 dB effective electro-optical bandwidths for the different scenarios are also detailed in Table 1, shaped by a fourth-order Bessel filter as well.

To evaluate the performance of the AOP, an equalizer employing 21 symbol-spaced taps of Feed-Forward Equalization (21FFE) and three taps of Decision Feedback Equalization (3DFE) is used. The primary performance metric in this simulated environment is the bit error rate (BER) analysis, which assesses the effectiveness of the AOP in optimizing signal integrity.

The tuning of the AOP’s parameters is achieved using a machine-learning-driven Bayesian optimization decider. A probabilistic model is employed by Bayesian optimiza-

tion [35] to identify parameter configurations that minimize the BER, leading to enhanced performance. The method starts with a broad exploration to gather performance data and progressively focuses on promising areas, ensuring efficient and effective optimization. Comprehensive control of the AOP’s behavior is taken by the decider. Dynamic switching between tasks (equalization or chromatic dispersion compensation) is performed based on current network conditions, and optimal values for sub-task components are selected. This dynamic selection ensures that a performance boost is tailored to each specific scenario. The optimizer sweeps various fiber lengths, accounting for different chromatic dispersion levels and optical power variations due to attenuation and dispersion, ensuring the parameters work universally across different fiber lengths while maintaining FEC limit performance. This dynamic selection, along with training across a range of fiber lengths, ensures the AOP’s adaptability to environmental changes such as temperature fluctuations and mechanical strains, which typically affect signal quality in real-world scenarios. Table 2 depicts the task and sub-task parameters that the ML decider algorithm chooses for each of the two simulated PON scenarios. The decider’s flexibility in managing the AOP is a key factor in boosting performance and robustness, allowing it to surpass even the most complex digital FFE and DFE systems.

Table 2. ML decider output values.

Parameters	Simulated 100G PON	Simulated 200G PON
Task (FFE/CDCF)	FFE	CDCF
Attenuators (dB)	24, 9, 20, 30	-
Phase Shifters (deg)	0, 0, 180, 180	146, -88, -158, -71
Optical Delay Lines (ps)	-	14, 16, 15, 24

5. Results and Discussion

The performance evaluation of the AOP for 100G and 200G downstream PON traffic is detailed in Figures 5a and 6a. To assess its performance, the AOP was tested both as a standalone module and in synergy with a minimum-complexity digital FFE. For benchmarking purposes, the proposed equalization techniques, as outlined in Table 1, were employed.

As mentioned above, the machine-learning-based decider selects the optimum task for each use case. In the case of 100G PON, Task 1 is selected, which comprises the optical FFE, whereas, in the case of 200G PON, Task 2 (CCDF) is chosen. For both cases, BER results were acquired against transmission distance and against receiver optical power at specific points.

For the case of 100G PON, it is evident from Figures 5a and 6a that the use of the AOP (Task 1) enhances the overall system performance compared to the digital 13FFE. Furthermore, the synergy of the AOP with digital five-tap FFE increases the transmission distance under the FEC limit by an additional 6 km, achieving a total fiber reach of up to 36 km. In terms of power penalty, the use of the AOP increases the ROP by about 3 dB at the FEC limit compared to the standalone digital equalization method. The depicted eye diagrams further support these findings, showing much clearer and more distinct eye openings when the AOP is used, indicating a substantial improvement in signal quality.

For the case of 200G PON, Figures 5b and 6b demonstrate that the AOP (Task 2) significantly enhances the system performance over digital equalization techniques. It is even more clear that, with the AOP alone, we can see a substantial performance boost, extending the transmission distance to 14 km instead of 11 km with the 21/3 DFE. This boosted performance is further enhanced by the addition of a five-tap FFE, making this optoelectronic solution reach a fiber distance of up to 17 km. Regarding the power penalty, the AOP combined with the digital 5-tap FFE reduces the power penalty by about 3 dB at the FEC limit compared to the 21-tap FFE and 3-tap DFE digital solution. The same applies to the power diagram, where we see an ROP improvement of 6 dB only with the processor,

and a similar performance with the addition of a five-tap FFE. The eye diagrams for the 200G PON also show significantly improved signal integrity.

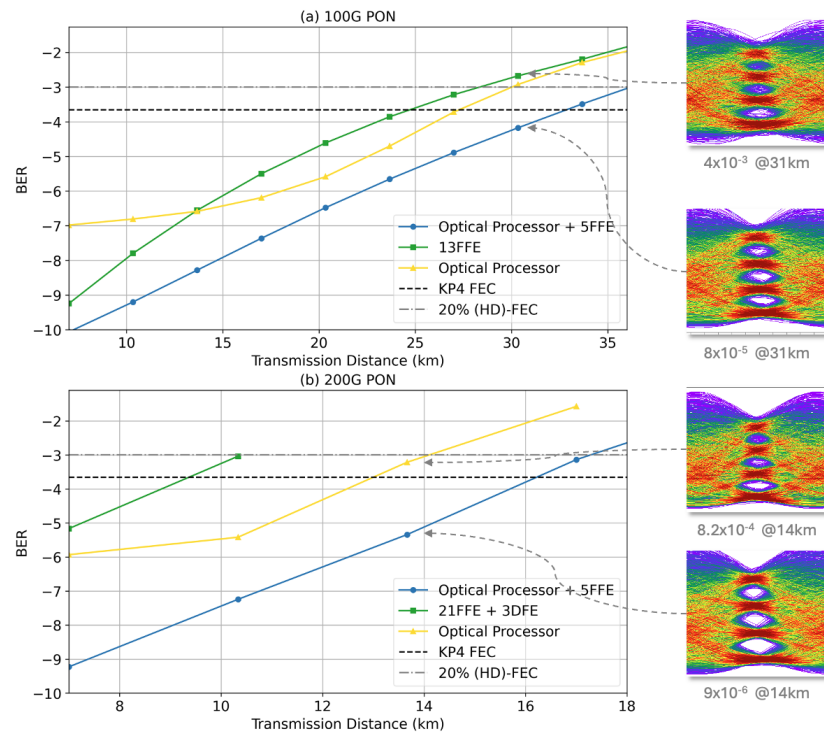


Figure 5. BER vs. transmission distance for (a) 50 GBaud PAM4 and (b) 100 GBaud PAM4.

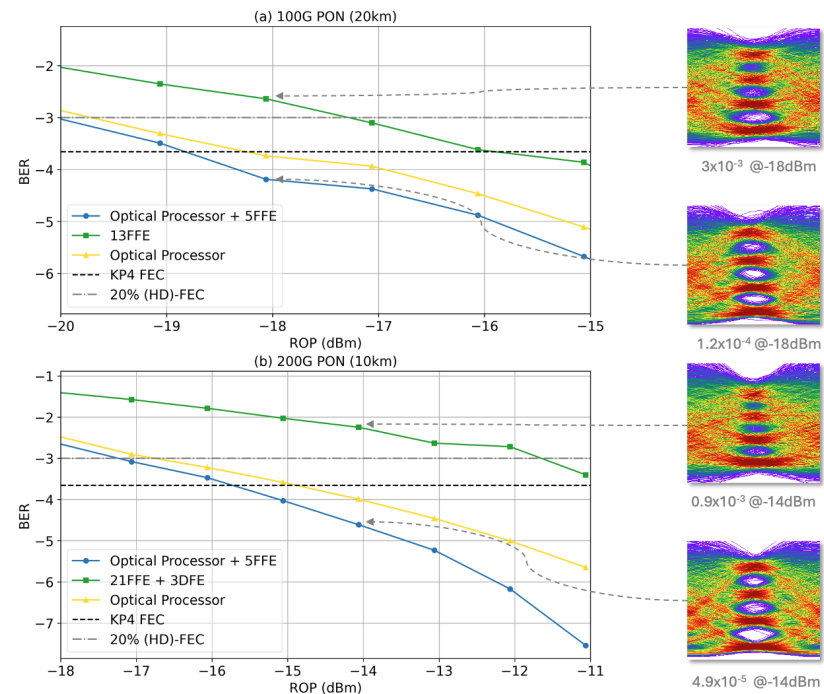


Figure 6. BER vs. ROP for (a) 50 GBaud PAM4 and (b) 100 GBaud PAM4.

Figure 7 illustrates the optical spectrum of the transmission system operating in two different cases (100G and 200G PON). Figure 7a shows the spectrum before AOP during Task 1, after the AOP, and before the receiver at 50 GBaud with an ROP of -14 dBm. Figure 7b presents the spectrum at 100 GBaud with the same traces (the only difference being that, this time, the decoder goes with Task 2) with an ROP of -11 dBm. The optical

spectra in both cases demonstrate the efficient utilization of bandwidth and the effectiveness of the AOP in maintaining signal integrity at higher data rates.

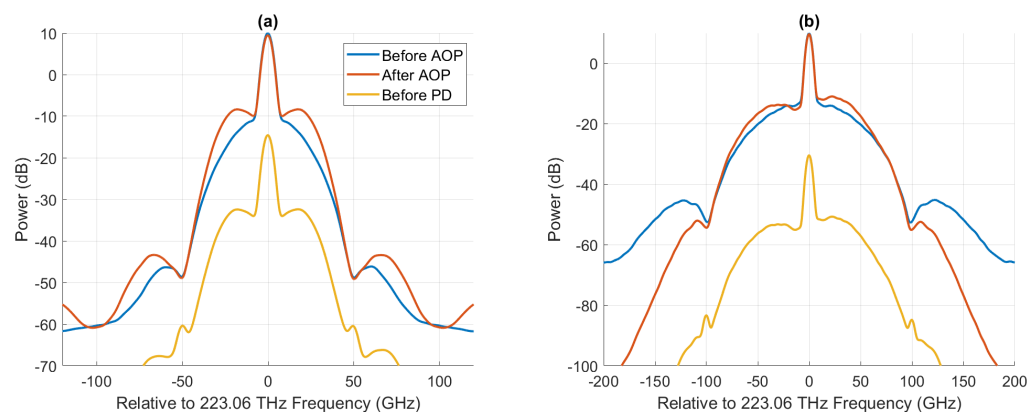


Figure 7. Optical spectrum: (a) 50 GBaud (ROP = −14 dBm) and (b) 100 GBaud (ROP = −11 dBm).

Regarding the implementation of the AOP, mature photonic integrated platforms already exist which can integrate the necessary optical components. Various methods for integrating these components effectively have been documented in the literature, whether utilizing InP [36–39] or Si [40–43] technology.

According to typical values reported in the literature, specifically for Si platforms, an estimation of the power consumption of the AOP can be provided. For Task 1, consisting of three delay lines, four attenuators, and four phase shifters, the estimated power consumption is 97 mW. For Task 2, consisting of four filters, four delay lines, and four phase shifters, the estimated power consumption is 122 mW. In comparison, classical DSP methods such as FFE and DFE often exceed 700 mW and can reach up to 1 W as baud rates increase [44,45]. Thus, the AOP is presented as a power-efficient solution, achieving superior performance at only 10% of the power consumption of its digital counterparts.

The results highlight the promising potential of the all-optical processor and the superiority of the combination of optical and electrical equalization in high-speed PON systems, ensuring higher ROP tolerance and longer fiber reach. With the help of the equalizer, the fiber reach can be increased, making PONs more suitable for broader deployment areas. More significantly, this increase in received optical power tolerance—at least 3 dB—could provide the flexibility to double the number of users that a single PON can serve. Consequently, this advancement not only extends the operational range but also enhances the scalability and efficiency of network deployments, addressing the ever-growing demand for high-speed, reliable internet access. This approach dictates that future PONs can rely on leveraging legacy IM/DD equipment to achieve cost-effective and high-speed solutions.

6. Conclusions

We present a novel all-optical processor designed to overcome the limitations of current high-speed PONs. This processor leverages optical signal processing techniques to perform either all-optical equalization or chromatic dispersion compensation, offering a significant improvement in system efficiency and power consumption. The processor effectively manages the increased computational demands of DSP by dynamically switching between tasks and selecting optimal parameter values, significantly boosting performance and surpassing the capabilities of its complex electrical counterparts. Experimental validation shows substantial enhancements in signal quality and overall network performance, demonstrating the processor’s potential for deployment in future high-capacity access networks. The proposed solution not only addresses the growing demand for higher data rates but also reduces the complexity and power consumption associated with traditional electrical methods. By integrating advanced optical techniques, this work paves the way for scalable and cost-effective implementations in next-generation PON technologies.

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